ROOT MORPHOLOGY AND DEVELOPMENT
IN
SELECTED SPECIES OF *CALAMUS* L. (Arecaceae)

THESIS
submitted to the
University of Calicut
in partial fulfillment of the
requirement for the degree of
DOCTOR OF PHILOSOPHY

by
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CERTIFICATE

This is to certify that the thesis entitled **Root morphology and development in selected species of *Calamus* L. (Arecaceae)** is a record bonafide research carried out by Mrs. Jayasree. V. K., under my guidance and supervision. No part of this work has been presented elsewhere for any degree, diploma, fellowship or other similar titles.

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DECLARATION

I hereby declare that the thesis **Root morphology and development in selected species of *Calamus* L. (Arecaceae)** submitted by me in partial fulfillment for the Ph.D degree of the University of Calicut, incorporates the results of the work done by me. This thesis has not been submitted by me to any other university for the award of any other degree, diploma or any other titles and it represents the original work done by me.

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1.

INTRODUCTION

1. INTRODUCTION

The genus *Calamus* L. coming under the subfamily Calamoideae of the family Arecaceae (Palmae) (Uhl & Dransfield, 1987) consists of trailing or climbing spiny palms with characteristic scaly fruits. This group of climbing palms are commonly called as "rattans", which yield the cane of commerce. Rattans constitute an integral part of the tropical forest ecosystem and include 13 genera and about 600 species in the world (Uhl & Dransfield, 1987). In India, rattans are reported to have 61 species under 4 genera – *Calamus, Daemonorops, Plectocomia* and *Korthalsia* (Renuka, 1999). Among them, forty two taxa are endemic to the country and are distributed in three centres viz. Peninsular India, North eastern India and Andaman & Nicobar islands. Peninsular India has only one genus, *Calamus* and in Kerala 15 species of this genus occur (Anto *et al.,* 2001).

The word 'rattan' is derived from the local Malay term 'rotan' used for canes (Whitmore, 1973). Rattans or canes were considered to be a very low value product, meant for inexpensive and often traditional furniture. But today, they are high value materials which are being over exploited and are in short supply. Because of their strength, flexibility and uniformity, the bare stems of rattans are used commercially for cane furniture and matting. Burkill (1935), Corner (1966) and Dransfield (1979a) have listed the various local uses of rattans. They are used in the making of baskets, mats, furniture, broom handles, carpet beaters, walking sticks, fish traps, animal traps and for almost any other purpose requiring strength and elasticity combined with lightness. Houses, fences, bridges and even boats are bound together with rattan, often without the use of a single nail. Ropes for tethering buffaloes, mooring ropes, anchor and bridge cables are also made from rattans. Rattan leaves are used for thatching. Consequently, this resource is being overexploited and has become short in supply. The rattan industries in South India are short of supply of raw material and are purchasing it from north eastern states and Andaman Islands at a higher price.

Rattans are restricted mostly to remote areas in Kerala and the broad genetic base is being reduced alarmingly. An imbalance between demand and supply, the former being more, large scale destruction of forests and unscientific exploitation have led to the disappearance of rattans from our forests. Effective measures are to be taken to conserve and propagate this endangered species. Ecosystem conservation together with large scale cultivation of rattans will guarantee enough raw material for the industry as well as the conservation of the species and genetic diversity.

The species of *Calamus* occur from almost sea level to 2000 m in evergreen, semievergreen, and moist deciduous forests. Ecologically, they are the indicators of the health of tropical evergreen forests. Survey in the forests of Kerala revealed that some of the species reported are threatened with depletion or extinction (Renuka, 1992; 1999).

The Kerala Forest Department has already started cane plantations and the areas may be extended during the coming years. Rattans are versatile in the sense that they can be grown easily in a variety of ecological conditions, and yield attractive returns apart from improving the ecology of forests. Since rattan is a new plantation crop, the silvicultural practices to be adopted are unknown. Standardization of silvicultural practices require a sound knowledge on the pattern and growth of the root system.

The root system anchors the plant in the soil, absorbs water and minerals, and serves as a store for carbohydrates. On its size, type and efficiency depend the competitive ability of an individual and the success of a species in any given habitat. Knowledge of the structure and development of the root system is essential for complete understanding of the ecological requirements of each plant, which in turn forms the necessary basis for silvicultural practices.

Root system of tropical plants is however little investigated. The existence of morphological and anatomical diversity in roots of tropical plants has long been known, but attention was inevitably focused on the more obvious aspects of root morphology of tropical trees, such as the development of aerial roots, especially in mangrove species (Troll 1937; Lyford and Wilson, 1966).

Roots account for between 40 and 85% of net primary production in a wide range of ecosystems from grassland to forest (Fogel, 1985). Typically plant growth in non-agricultural conditions is limited, more by soil-derived resources than by CO_2 or solar radiation. (Fitter, 1986). It seems axiomatic, therefore, that an understanding of the functioning of plants within natural communities must demand an equal understanding of the behaviour of roots and root systems.

Roots are much less variable morphologically and it is likely that root systems rather than individual roots are the focus of natural selection. An ecological perspective of the functions of root systems must therefore concentrate more on the morphology of root systems than on that of individual roots.

Individual roots in soil vary greatly in size, longevity and activity and their interaction with other organisms will depend on these variables, many of which are determined by the relationship of the root to the whole root system. The function and activity of root system is closely linked to their normal environment – soil. ‘Root morphology and distribution’ has been identified as a balance between systematic biological mechanisms and their disruption by environmental factors, particularly changes of soil density and soil surface contours.

Study of root morphology is therefore important in understanding the interaction and dynamics within the soil system.

In the study of soil-plant relations, in addition to the geometry of individual roots (length, diameter, volume and surface area), the spatial distribution of roots in the soil, also, is of great importance, because the orientation of root axes determines the ability of the root system to retain the plant in an upright position. It can influence the efficiency with which the soil is exploited. Besides, the extent of root spread should be taken into consideration when silvicultural operations are carried out.

Two basic elements in morphogenesis of a plant root system are 1) longitudinal growth, which forms the basic frame work, and 2) subsequent radial growth, which leads to thickening of the frame work. The development of large root systems by vertical and horizontal extension and branching is important to the success of plants, especially when the soil water content falls much below field capacity. Thus, a vegetation unit is dependent on a volume of soil for supply of water and mineral resources and for physical support. One should become aware of the extent of roots of species and the general rooting depth of vegetation. The depth of rooting and extent of branching are thus important in choosing plants for soil stabilization and watershed cover. Monocot root systems comprise of many root axes and their branches. These root systems are generally called 'fibrous' roots because of the massive body of small wiry roots in the top 10 to 20 cm of soil. These root axes originate from nodes either in the seed (seminal roots) or in the crown (adventitious or coronal roots). Generally, the seminal root system services the shoot until the crown root system is produced, beginning at about the three leaf stage (Klepper *et al.*, 1984; Newman and Moser, 1988).

The primary root in palms as in other monocots is formed in embryogeny, but it is short lived, because it gets soon arrested and is replaced by adventitious roots arising from the basal nodal plate in the embryo. Several adventitious roots arise in quick succession. Very often, the embryonic root, with embryonic stem and its growing point are pushed out of the seed by a haustorium or a sucker, sometimes by a distinct collar as in *Caryota* or by a haustorial tube. There are 2 distinct types or modes of germination in palms, admotive and remotive. In the admotive type, the embryo grows *in situ* as in *Cocos nucifera* or *Nypa fruticans* and in the remotive type, it grows outside further away as in *Lodoicea maldivica*.

The roots in a fully grown palm are all adventitious. They arise from the lower part of the tree trunk from the semi circular or obconical portion of the base of the underground stem. However, they pierce their way out through the hard trunk. They may either enter the soil and function as normal absorbing roots or without entering the soil, they may function as aerial adventitious roots. They form a kind of mantle or girdle of short stiff roots around the stem. Some of them after having entered the soil, grow a few metres beyond. They may also form secondary branches. The number of adventitious roots in palms with a big trunk runs into several thousands. But in reedy palms, the number of roots is much less; in palms like *Calamus*, they are few but very strong and stout.

All palm roots arise adventitiously. They are usually of 4 kinds – 1) aerial roots functioning as prop or stilt roots 2) aerial roots forming a mantle around the stem 3) pneumatophores and 4) normal absorbing roots.

In rattans, no detailed study on root system has been carried out so far and hence not much information is available on the growth pattern, the nature or branching pattern and the spatial distribution of roots. especially in the seedling stages, which is essential for optimizing the silvicultural practices in the nursery and early growing stages, like the size of the polybags, the size of the pit for outplanting, the size of the basin to be opened around each plant, the radius and depth for fertilizer application etc.

Volume of soil available for rooting is an important factor governing the growth of seedlings. Only a small fraction of the soil within the rooting zone is in direct contact with roots and this determines the amount of nutrients the plant can absorb which in turn is responsible for its growth. An idea regarding the effective soil volume, that is, the volume of soil that is able to supply water to a root system and that does not restrict the growth of these roots, will help in regulating silvicultural practices.

The form of the root system not only influences, but is also influenced by the absorption of nutrients. Rooting density of a plant is seen to be responsible for the gradients of water potential at the root surface which in turn influences the uptake of minerals.

Root intensity obtained by counting the root number in unit area of soil is yet another method of studying distribution and function of roots in the soil.

Root surface area considered as a root parameter measures the total absorptive area of the root and is especially important in the supply of an immobile nutrient to the plant. Soil binding capacity which is the measure of the binding effect on the soil particles is of direct value in soil conservation. Fine roots of certain plants, with their close and elaborate network have good binding capacity on the soil thus making them suitable in conservation forestry.

A knowledge regarding the above mentioned aspects of rattan root system will aid management decisions and optimizing silvicultural practices.

Root system usually comprises not more than one quarter of a seed plant, but the roots are so finely divided that frequently they occupy a mass of soil greater than the volume of the atmosphere occupied by the shoot. The result is a tremendous amount of surface contact between soil and plant, which is very important in view of the plant's dependence upon the soil for anchorage, water and nutrients. The soil (edaphic) factor deserves much attention because owing to this intimacy of contact, plant and soil are strongly influenced by each other.

Root systems are, important for water and nutrient uptake, sources of endogenous hormones, and ultimately have direct influence on seedling growth and development. Seedling root morphology, development and growth can directly affect rates of seedling emergence and shoot development. Root systems and root morphological components (tap roots, basal roots, adventitious roots and lateral roots) although genetically controlled, are very variable in growth and development even in optimum environments. Therefore, fluctuating soil environments (soil pH, moisture, temperature and nutrients) may have major impacts on root growth.

The concealment of roots by the soil introduces an obvious complication into the study of this subject and further, difficulties often arise from the variable nature of the soil. Different parts of a single root system frequently experience widely contrasting environments which can change rapidly depending on weather.

Understanding seedling root and shoot relationship, particularly following exposure to abiotic stress, can assist in developing and utilizing cultural and/or management practices for optimum seedling growth and crop yields. (Stoffella *et al.*, 1998).

The present study is chiefly concerned with the general form which the root system can attain and its distribution under relatively favourable conditions, with the main objectives being

1) to study and compare the development of root system, rhizome and the spatial orientation of roots of the selected species of *Calamus* from the germination of seed onwards,

2) to determine and compare the utilization of soil by the root system,

3) to compare the efficiency of the root system,

4) to find out the relation, if any, between the root growth and the soil characteristics.

The early stages of growth are mainly considered because root development at that time is more likely to affect the survival of the plant.

Chapter 2.

REVIEW OF LITERATURE

2. REVIEW OF LITERATURE.

Roots, the hidden half of plants, even though serve a multitude of functions, are still an 'enigma' to scientists in various aspects. Root research, under natural field conditions, according to Böhm (1979) is a stepchild of science. It is in fact a truth that the root system of tropical plants, though vary greatly in their form, are little investigated. The existence of morphological and anatomical diversity in the roots of tropical plants has long been known, but attention was inevitably focussed on the more obvious aspects of root morphology of tropical plants, such as development of aerial roots, especially in mangrove species.

Under monocots, considerable amount of work has been carried out in cereals . The different aspects studied were origin and development of root systems including methods for root studies in field experiments, origin of seminal roots, initiation of lateral roots, their distribution pattern, root system extraction and preservation, quantification of the different root parameters, functions of root systems in correlation with the rooting pattern, root system in relation to shoot system and root- soil interaction. However, not much studies were conducted on the root systems of palms. For the sake of convenience, the literature review has been dealt under the following headings:

2.1) Studies on root morphology 2.2) Studies on roots in Arecaceae and 2.3) Studies on root-soil interaction.

2.1. STUDIES ON ROOT MORPHOLOGY

An ecological perspective of the functions of root systems must concentrate more on the morphology of root system than on that of individual roots. There are a number of features that play a large role in determining the overall form of root systems, the important ones being balance of primary and adventitious roots, degree of branching and plasticity of branching (Fitter, 1987). Here studies on root morphology in the monocotyledonous families has been dealt under different headings like 2.1.1) methods for root studies, 2.1.2) general root system 2.1.3) root distribution, 2.1.4) root parameters, 2.1.5) root system in relation to function and 2.1.6) root shoot interrelationship. The studies on *Arecaceae* have been dealt with separately.

2.1.1. Methods for root studies

The main problem in studying the behaviour of roots in nature is that it is impossible to observe a root growing in soil. Most of the studies are conducted in water culture and other artificial media. The use of water culture as a growth medium is the easiest but least meaningful since the fundamental character of soil is that it is heterogeneous. Devices like glass fronted boxes or , rhizotrons with glass viewing panels concentrate the observed root system into two dimensions or allow only very small region to be observed. Hence more energy has been spent on developing technologies than on studying roots. But each method so far developed has serious shortcomings.

Blaser (1937) proposed a rapid quantitative method of studying roots growing under field conditions. Soil prisms obtained at different depths were trimmed and the roots present were washed free of soil. The roots washed free of soil were then sectioned to correspond with various soil levels to determine relative distribution of roots at various depths. The advantages of the method were that quantitative results were obtained and the method could be used for obtaining material for root reserve analysis. The method was especially adapted to soil types which prohibited deep rooting of plants and was especially useful for studying densely rooted areas where individual roots were traced with difficulty.

According to Smucker (1993) appropriate methods for quantifying root morphology were a function of the experimental objectives.

Root length could be estimated by direct measurements, intersection methods or by photoelectrical methods. For direct measurements, the wet roots were placed in a flat glass dish containing a small amount of water. Graph paper, ruled in millimeters was placed under the dish. The roots were straightened with forceps so that they did not overlap and were held in position by a glass plate. The length of the given roots or root segments were then estimated to the nearest millimeter by eye- inspection or by the use of a magnifying glass. (Dittmer, 1937,1938,1948,1959; Spencer, 1951. and Cockroft and Wallbrink, 1966). Instead of arranging the roots randomly in a dish, every individual root could be dipped into gum and mounted end to end in lines on graph paper ruled in millimeters. Roots, if branched were cut into individual segments before glueing. (Nutman, 1934; Barua and Dutta, 1961).

The line intersection method as described by Newman (1966) is a method of estimating the total length of root in a sample. The roots were laid out in a flat surface and a count was made of all the number of intersections between the roots and random straight lines. Total root length was calculated using the formula, $\frac{IINA}{2H}$, where *'N'* was the number of intersections, *'A'*, the area within which the roots lie and H, the total length of the straight lines.

Melhuish (1968) proposed a precise technique for measurement of roots and root distribution in soils. A procedure was discussed in the paper in detail, which yielded directly the complete spatial distribution and sizes of roots in soils, and so provided such information as the length and area of root per unit volume, the number of root tips per unit volume and the proximity of roots to one another. The method involved stabilization of the soil by vacuum impregnation with plastrene 47 and examination of the serial surfaces proposed by surface-grinding using both visible and ultraviolet fluorescence photography.

The simple technique outlined in a paper by Gooderham (1969) presented a root system '*in situ*' in three dimensions so that it could be easily studied, photographed and preserved. The method was suited for an undisturbed root system, which was extracted from a soil core. The support for the root system was provided by a nylon mesh, which was replaced by gelatin, the whole being transferred into a Perspex box.

Lang and Melhuish (1970) considered the theory associated with an experimental procedure for estimating the length of plant roots in soil by calculation from the frequency at which roots intersect planes cut through the soil.

Reicosky *et al.* (1970) made a comparison of three methods for estimating root length in soyabean – a dicotyledonous plant. The root system from a 10-week-old soyabean plant was washed free of soil and total root length estimated by three different methods. Direct measurements were made on fresh root samples and from projected black and white photograph transparencies of the fresh material. Estimates of root length were also obtained by obisometer method, which in essence, required tracing over the entire length of root in a sample and also by intersection method. The coefficient of variation for means of the three estimates by each method showed that there was little difference in precision between the methods.

Marsh (1971) in his paper argued that Newman's (1966) formula for measuring root length using intercept method could be simplified to R=11/14 N for a grid of indeterminate dimension. N comprised all intercepts of roots with the total length of vertical and horizontal grid lines and R is measurable in terms of grid units.

Tennant (1975) developed a method of length estimation based on Newman's (1966) line intersect principle and tested during a programme of root growth investigation in wheat. The length of sample roots when spread over a flat surface was found to be related to the number of intercepts made with the vertical and horizontal lines of an underlying grid. The versatility of the method was tested using ½ x ½ , 1 x 1, 2 x 2 and 3 x 3 cm grid square sizes.

Based on the consideration of Marsh (1971), Tennant (1975) argued that Newman's (1966) formula could be simplified. For a grid of indeterminate dimensions, the intersection counts could be converted to centimetre measurements using the equation:

Root length =11/14 x Number of intersection (N) x grid unit.

According to Tennant, the 11/14 of the equation could be combined with the grid unit and thus a length conversion factor was obtained. The factors for the 1, 2 and 5 cm grid squares were 0.786,1.57 and 3.93 respectively.

Tennant (1975) obtained good results using Newman's method(1966) and recording single counts when the edges of the curved roots touched a line and double counts in cases where roots were lying along a grid line.

Root length at natural soil profiles was estimated *in situ* by Böhm (1976). A thin layer of soil was washed from a smoothed soil profile and the length of the roots visible at the profile wall estimated. A grid net was used to count every visible part of a root, which was nearly 5mm long. Roots, which were longer than 5 mm, were counted more than once.

Diameter of smaller roots was measured directly on freshly washed root samples with the aid of a microscope fitted with an ocular micrometer. For large roots, a small hand less, a micrometer screw or calipers graduated to tenth of a millimeter could be used. If individual roots differed in diameter, they were measured at regular intervals throughout their length.

Melhuish and Lang (1971) described an improved method for estimating a number of parameters of soil grown roots by measurement in prepared plane surfaces of plastic-impregnated soil samples and application of geometrical probability theory. Automatic data collection and processing allowed the estimation of statistical confidence limits. Results were reported for both isotropic and anisotropic model populations and for samples from two different root populations. The procedure had wide application and was used for studying root distribution in agronomic experiments.

Kolesnikov (1971) classified the methods of study as excavation methods, monolith methods, auger methods, profile wall methods, glass wall methods, indirect methods, container methods etc. Of these, the traditional excavation method, also referred to as the skeleton method, was the oldest method used in ecological root research.

An autoradiographic method for measuring the root density and pattern of interpenetrating root systems was employed by Baldwin and Tinker (1972). They suggested that such measurements might give information on the mechanism where by root systems influenced each other. The root length per unit volume and spatial pattern were the two parameters obtained directly from the autoradiograph.

A technique was described by Batcheldor and Bouldin (1972) for accurately and automatically measuring the rate of elongation through soil layers having different physical or chemical properties, or both, without disturbing the root systems. Utilizing the electrical conductance properties of a root, the time at which the tip of an elongating root penetrated a paraffin-petroleum membrane separating two successive layers was determined by the resultant changes in electrical resistance between the two soil layers.

Ellis and Barnes (1973) described an autoradiographic method, which does not involve separation of roots from soil, for estimating the relative distribution of living roots of graminaceous plants (*Hordeum vulgare* and *Lolium perenne*) growing under natural field conditions. The method involves injecting ^{86}Rb into the base of shoots.

Bloomberg (1974) adopted Gooderham's methods suitable for field grown and potted plants for examining and recording small plant roots with minimum disturbance.

Comparisons of distribution with depth of roots were made by Lupton *et al.* (1974), estimation being made by injecting rubidium into stem bases and counting the content in soil cores. The relative ability to absorb phosphate from different zones was measured from the recovery in aerial parts of ^{32}P injected into the soil at different depths. The distribution of dry matter in roots and aerial parts, and total root length, was measured using soil cores and samples of aerial parts taken during the growth of the crop.

Root weight was commonly determined as a criterion of root response to the environment. Al-Khafaf *et al.* (1977) studied the distribution of cotton roots with depth and time by soaking soil and roots in a solution containing 40g/litre sodium hexametaphosphate in a 1:5 soil solution ratio. The density of the resulting soil suspension was then increased to 1.5 g/cm^3 by adding dry, 78% pure $CaCl_2$ in a ratio of 1 g $CaCl_2$ to 2g soil suspension. Roots floated to the surface and were then skimmed from the surface with a fine wire strainer. By subsequent washing in tap water, roots and organic debris were separated.

Dunsworth and Kumi (1982) used mitotic index technique to quantify root activity. It appeared sensitive enough to discriminate between species and perhaps among stock types.

An autoradiographic method for studying the distribution of root system in the root space was described by Fusseder (1983). The technique was proved to be particularly of use in determination of the average distances between roots.

Veresoglou and Fitter (1984) determined the length of roots in each sample by automatic modification of the line intercept method.

Image analyzing computer, a particularly powerful tool was used for photoelectric measurement of root specimens. Roots in the soil core samples were washed free of soil and screened, stained and photographed shortly after removal from the field. Photographic negatives could be stored and analyzed by the image analyzer at a more convenient time.

Photocopying was found to be a rapid method of making a permanent record of a root sample (Collins *et al.*, 1987). The method used produced a copy with white roots against a black background. Manual estimates of root length were made from photocopies using a light box. The number of intersections visible when laid over a copy of a white on black regular square grid was counted. Automated estimate of root length was made by scanning a photocopy with a bar code reader in place of a pen in a computer driven graph plotter. Roots > 0.2 mm diameter were resolved with precision and speed.

Chain methods (Dorst and Smeulders, 1987) assumed random orientation of objects and counted the perimeter orthogonal and diagonal pixels separately. The MPO estimator (Dorst and Smeulders, 1987; Pan and Bolton.1991) averaged overall angles.

The line intercept method (Newman, 1966; Harris and Campbell, 1989) assumed random orientation of objects, with all angles being equally represented; and it was used by all laser-based root scanners as well as some image analysis methods. Typically, root length was calculated from the number of root intercepts along parallel scan lines. A modification by Harris and Campbell (1989) scanned in two directions and could handle slightly non-random distribution.

Software for an inexpensive hand-held scanner for the determination of root length, thickness and distribution of thickness was described by Kirchhof (1992) and Kirchhof *et al.* (1991). The technique employed an inexpensive hand-held scanner, an IBM- compatible personal computer and the line intercept of Newman (1966).

The boundary cord method (Ewing and Kaspar, 1993) was a perimeter tracking algorithm that identified the edges of “steps” in the digitized images and then measured the straight-line distance between step edges. It was concluded that the automated methods of measuring sample lengths were generally good when their coefficient of variation were compared with coefficient of variation of root samples.

Mackie- Dawson and Atkinson(1991) reviewed different methods available for the study of plant root systems in the field especially in relation to those methods which were appropriate to studies of natural plant communities or where major advances in technology had occured. They divided the available methods into three major groups:

1) Soil sampling methods
2) Observation methods
3) Indirect methods.

The advantages and disadvantages of the different methods were also discussed in respect of the biological and ecological significance of the data generated. According to the authors the main criterion influencing the selection of a method was probably whether information was needed on changes with time or whether spatial data on distribution at one moment in time would be adequate.

Polomski and Kuhn (1998) discussed methods to study root system, root spatial distribution in soils and root growth as dependent upon exogenous and endogenous factors.

Mckell *et al.* (1961) described a floatation method for easy separation of roots from soil samples. Improvements on his method included a pressure stream of water to wash and circulate the soil root water mixture, the use of a relatively small volume of water, and an assembly-line arrangement of root washing units.

2.1.2. General root system

The roots of monocotyledonous plants increase their length without radial change as they grow. This implies that they were initially sub-optimally efficient structures, tending towards optimality. Once the root system of monocots develop and optimum conditions are realized, development stops and to be more efficient, the plants extend other (non-optimal) parts of the root system or produce new roots to meet their water requirements. Monocotyledonous system is much less flexible than the dicotyledonous system.

Hoshikawa (1969) studied the underground organs of Gramineae seedlings to establish relationships between seedling root morphology and the systematics of grasses. He classified 219 species into six seedling types based on root morphology and noticed that nearly all species of the same genus were of the same seedling type.

The pattern of axis production and growth in cereals was such that successive axes explored wider and wider cylinders of soils as the seasons progressed. Generally the seminal root system serviced the shoot until the crown root system was produced beginning at about the three leaf stage - (Klepper *et al.*, 1984; Newman and Moser, 1988). Mc cully and Canny (1985) noted that on field grown maize plants, laterals of older seminal roots exhibiting already dead tips remained functional.

Fusseder (1987) described the development and longevity of the seminal root system of maize under controlled green house condition with particular regard to the laterals. The investigation showed that the primary root of maize persisted during the whole life span of the plant. However, the longevity of the different tissues and structures of the primary root varied considerably. Mean root length of laterals decreased with increasing root age.

Newman and Moser (1988) discussed the seedling root development and morphology of cool season and warm season forage grasses. The seedling root development and morphology of a group of economically important forage grasses were studied. The usage of different terms like seminal roots, adventitious roots, permanent roots, cotyledonary node roots, transitionary node roots and crown roots were discussed. Cool-season grasses had little sub coleoptile internode root development. The juvenile root mass of two species having similar number of seminal roots differed which was due to the difference in the relative size and branching of the seminal and primary roots. Adventitious root dry weight was much greater for the cool season grasses than for warm- season grasses.

Halle *et al.* (1978) concluded that the radicle or seedling root in monocotyledons was always short lived since it was capable of only primary growth, consequently no matter how much it could extend its absorptive area by distal branching. Its attachment to the seedling axis represented a bottleneck and the seedling root alone could not supply the increasing needs of an enlarging axis and crown. The obconically elongating axis, however provided an increasing area for the insertion of numerous adventitious roots so that the potential bottleneck was by-passed.

Klepper and Rickman (1990) noticed that at germination, the radicle usually grew vertically downward and was followed by other axes from successive nodes on the plant.

Formation of crown root promordia in lower part of unelongated stem of rice plant was noticed by Nitta *et al.* (1996).

2.1.3 Branching pattern and distribution of roots

Generally, some aspects of root architecture are under genetic control. The ability of an embryo to generate a tap root or not is clearly deeply seated in the phylogeny of the species and species differ widely in their ability to produce roots from the stem nodes. Seedlings of Sorghum sp. usually produced only one seminal root, where as maize usually produced three and wheat five. Roots commonly appeared from the stem above ground in maize. Thus species-specific differences existed between the architecture of root systems.

The architecture of roots was much less tightly canalized than that of shoots thus being more plastic than that of shoots. The most striking aspect of the plasticity of root development was their extremely localized branching response to local environments within the soil, in particular their ability to branch profusely within very local pockets of organic matter.

Bose and Dixit (1931) placed root systems of barley according to the character of its shallow roots and deep roots in one of the four classes namely 1) Mesophytic type of root system

2) Semi-mesophytic type of root system 3) Semi-xerophytic type of root system and 4) Xerophytic type of root system.

Relative distribution of roots at various depths of soil was determined in plants growing under field conditions by Blaser (1937).

Leonard (1957) suggested that laterals developed in series of four or six on the seedling root with a precise orientation in relation to the cotyledons, suggesting the expected relation with anatomy. The existence of regular series of plagiotropic laterals in root system suggested that it might be possible to recognize “architectural models” in root systems comparable to that in the shoot systems.

The horizontal spread of lateral roots varied with the size of the crown, stocking density and age of tree (Mc Minn,1963). The degree of occupation of a soil volume by roots which depends on the branching and distribution of minute roots, serves as a criterion for distinguishing intensive and extensive types of root system.

Riopel (1966) concluded that the initiation of lateral roots in banana was not a random phenomenon, which could occur equally well at any protoxylem position on the pericycle. A certain amount of regulation for lateral development which could not be explained simply by the existence of special conditions at the protoxylem poles or by the presence of balance of metabolites along the main root axis existed. However, certain protoxylem positions were more favourable than others and those sites were often related to the position of the previous lateral.

Major works on root distribution were that of Melhuish (1968), Melhuish and Lang (1971) Baldwin and Tinker (1972) Batcheldor and Bouldin (1972) and Fusseder (1983).

The patterns and extent of root growth reflected both the genetic control of the plant and characteristics of the soil environment. Degree of root branching and other growth characteristics exhibited both interspecific and intraspecific differences in the same environmental setting, which indicated that root growth in part followed a genetic programme. (Hackett, 1969; Troughton and Whittington, 1969).

Hackett and Bartlett (1971) described four characteristics of the branching pattern of barley roots. The morphology and nutrient absorbing activity of root system of barley (*Hordeum vulgare* L.) grown in water culture as affected by age, variety and nutrient supply was also described. The most striking observations were a) 50-75% reduction in the length of unbranched axis caused by nutrient deficiency suggesting that emergence of laterals was hastened b) marked curvilinearity in the profile under all nutrient treatments and c) high dependency in the form of the profile on variety and nutrition.

Ellis and Barnes (1973) estimated the relative distribution of living roots of graminaceous plants (*Hordeum vulgare* and *Lolium perenne*) growing under natural field conditions.

Lupton *et al.* (1974) made comparisons of the distribution with depth of roots.

Atkinson *et al.* (1976) found that with increasing planting density, the root system changed from a framework of mainly horizontal roots with a few vertical sinkers to one of mainly of sinkers where a much higher proportion of roots were present at depth.

The density of roots in the soil increased with increasing planting density. To summarise, the actual contribution made by different root types depended upon the relative lengths of the different root types, their distribution with depth, contact with soil and the extent to which they were affected by adverse soil conditions.

The root system usually occupied a soil volume determined in part by genetics, environmental factors and plant density. (Nye and Tinker, 1977; Russell, 1977).

When a plant root met interface within soil, either it was deflected or it penetrated the interface and entered the new medium. (Dexter and Hewitt, 1978). It was concluded that the deflection behaviour of roots which were not limited for water or air depended strongly on the mechanical and geometrical properties of the soil and might be very similar for different plant species.

Atkinson and Wilson (1980) suggested that root distribution modified nutrient uptake although its effects appeared only when the tree was under stress or when demand was particularly high. Atkinson (1980) concluded that the root system of a tree differed from that of an annual plant in its perenniality accumulating during its life, a framework of roots ramified through out the soil volume. Later formed roots could thus be produced in any part of the profile without the need for growth from the trunk although this occurred initially and when renewal was needed.

Charlton (1983) discussed the patterns of distribution of lateral primordia in *Pistia stratiotes* and *Potentilla palustris*. The major feature of the distribution pattern was a rather regular spacing along protoxylem based ranks. In *Pontederia* and banana, lateral roots were initiated within a very short distance of the root cap junction.

The growth, activity and distribution of the fruit tree root system was studied by Atkinson (1983). Fogel (1985) reported that the roots of monocotyledonous plants such as barley were small and fairly uniform, ranging in diameter from less than 0.1 to 0.7 mm. After germination, the root system developed by repeated branching, producing seminal axes, nodal axes, laterals and sub laterals. The root distribution pattern in bamboo was studied by Mohankumar and Divakara (2001).

Branching pattern in onion adventitious roots was studied by Pulgarin *et al.* (1988). The paper dealt with the distribution pattern of lateral roots in *Allium cepa* in relationship with the vascular system of the mother root. The possible implication of factors originating in the mother root tip, the vascular system or from the developing lateral roots itself in establishing positional control in the adventitious root branching pattern was also discussed.

Root system of different varieties of rice was quantitatively characterized by calculating the amount of root and root depth index, an index of root distribution. (Morita *et al.,* 1995).

According to Charlton (1996) the initiation and development of lateral roots provided important means of constructing a root system increasing its absorptive area and the volume of substrate exploited.

Information on root morphology, root-shoot ratio and distribution of roots in relation to soil depth and plant growth stages were presented by Fageria *et al.* (1997).

2.1.4. Root parameters

In order to have a clear understanding of root health and function, it is essential we know more beyond contemporary single parameter approaches. Such single parameter approaches might be one of the reasons, which greatly limited our understanding of the complexities of certain aspects at least. Hence, for interpreting root data, it would be better to measure more than one parameter. The parameters commonly used to express root growth and distribution are number, weight, surface area, volume, diameter, length and the number of root tips. The work carried out with respect to these parameters have been reviewed in the following paragraphs.

i. Root weight

Root weight is commonly determined as a criterion of root response to the environment. In ecological study, dry weight is usually preferred. Much information concerning the growth and function of the roots is still based on dry weight. The simplest manner of obtaining the fresh weight is by blotting roots with blotting paper. To determine dry weight, the roots were first washed and the washed roots were then dried and weighed. The drying was done at 60 to 75° C, so that it prevented the roots from being pulverized (Schuurmann and Goedewaagen, 1971).

Evaluation of the roots of corn at 28 and 35 days after planting showed that total root weight, root volume and weight of nodal roots were significantly and positively correlated with root clump weight and root pulling resistance of mature plants under field culture (Nass and Zuber, 1971).

Determination of root weight by soaking soil and associated roots, and washing over sieves often resulted in losses of root material. Al-Khafaf *et al.* (1977) made an improvement over this method by means of which roots and organic debris were separated.

Ennik and Hoffman (1983) discussed the root mass of grass under varied conditions. It was shown that root mass of grass in monoculture varied widely with intermittent nitrogen supply. Root mass was found to be positively related to competitive ability.

For quantitative characterization of the root system of different varieties of rice, the length and weight of roots at different soil depths were measured and the number and growth angle of nodal roots were also examined from which amount of root and root depth index were calculated.

ii. Root length

Root length could be estimated by direct measurements, intersection methods or by photoelectrical methods. Direct measurements were done by Dittmer (1937, 1938,1948,1959), Grosskopf (1950) and Spencer (1951).

By intersection methods, root length could be calculated more rapidly by counting the intersections between roots and a regular pattern of lines. Head (1966) counted the total number of intersections between the roots and the vertical and horizontal lines of a grid on the glass observation windows.

Works of Grosskopf (1950), Gardner (1964), Taylor and Klepper (1973, 1975), Reicosky *et al.* (1970), Marsh (1971), Tennant (1975), Böhm (1976), Veresoglou and Fitter (1984) and Collins *et al.* (1987) with respect to root length estimation have been dealt in the section on “methods for root studies”.

iii. Root number

Root numbers counted in the different soil layers generally gave a good impression of the rooting density in a soil profile. In studies where the entire undamaged root system of a single plant was extracted, the number of main and lateral roots were counted to provide an estimate of their total length. (Dittmer, 1937, 1938; Pavlychenko, 1937a, 1937b). Although root number was not an ideal parameter, as long and short roots were regarded and counted as equal units, high correlations with other root parameters were possible (Melhuish and Lang, 1968; Köpke , 1979).

iv. Root diameter

A knowledge of the diameter of roots gave important information on the relationship between the pore size in a soil and the potential of root in penetration (Wiersum, 1957). Roots were divided into several classes according to their diameters. However, the classification was regarded as arbitrary. The common practice of dividing tree roots into classes with different diameters is an aid to obtaining information on the amount of fine small, medium and large roots in a root system. Root diameter was measured directly on freshly washed root samples with the aid of an ocular micrometer, a micrometer screw or calipers.

2.1.5. Root systems in relation to function

Root systems are complex structures, typically being composed of thousands of individual root tips and different classes of roots that vary developmentally, physiologically and morphologically.

Spatial orientation is of considerable importance as it could influence the efficiency with which the soil is exploited. Local depletion of water and nutrients occurs more rapidly when several root members are in near proximity. According to Dittmer (1937) and Weaver (1926), the orientation of root axes in cereals influenced their ability to retain the plant in an upright position. If the axes subtended a wide angle, the stability of the plant and its resistance to root lodging was greater.

Water and mineral salt supply of a tree was primarily decided by the quantity and activity of fine roots (Grosskopf, 1950; Buchholz and Neumann, 1964). Soil exploration and exploitation proved amenable to quantitative investigation. Bray (1954) recognized the importance of ion mobility in soil controlling ion uptake by plants. The degree of occupation of a soil volume by roots which in turn depends on the branching and distribution of minute roots served as a criterion for distinguishing intensive and extensive types of root systems.

In addition to providing mechanical fastening in the soil and absorbing water and mineral salts, roots are highly specialized organs in which numerous syntheses are performed. (Mothes, 1956). Water uptake and mineral absorption, according to modern concepts are closely related to metabolic activity and growth of roots.

Bhimaya *et al.* (1956) remarked that the greater the volume of roots produced, the greater would be their mean length and hence, their power to go round the soil particles and bind them. Binding index was determined using the formula $F\infty\frac{W}{r^2}$, where *'F'* is the binding factor, '*W*' weight of roots in gms in unit volume of soil and *'r'* average radius of roots in millimeters. The horizontal spread of lateral roots varied with the size of the crown, stocking density and age of tree.

In orchard trees, the horizontal expansion of the root system was normally one and a half to two times as large as the crown diameter (Kolesnikov, 1962).

Studies on the seminal roots in *Phleum pratense* revealed that seminal roots had no physiological significance since nutrient uptake and growth were restricted if nutrients were supplied only to seminal roots (Williams, 1962).

Total root length was always important for phosphorus uptake and in a competitive situation, for potassium and nitrogen too. (Andrews and Newman, 1970). Newman and Andrews (1973) found that potassium uptake per unit root length decreased with increasing root density.

Roots deep within the profile usually extracted water more effectively per centimeter of root, than do roots near the soil surface. (Taylor and Klepper, 1973). It was suggested that the increased effectiveness of deep roots probably resulted from the deeper roots being younger, less crowded and often located in wetter soil. At high root density, there was a tendency for the flow rate of water and mineral nutrients to be low, and gradients at the root surface was found to be rare (Newman, 1969; Newman and Andrews, 1973). Atkinson (1974) noted a good correlation between the root growth and phosphorus uptake in young apple trees.

The relative ability to absorb phosphate from different zones was measured from the recovery in aerial parts of ^{32}p injected into the soil at different depths in semi dwarf and taller varieties grown in contrasting soils. There was little evidence of varietal differences in root growth, though there was some indication that at depth the roots of the semi-dwarf varieties were more extensive and absorbed more phosphate than those of the taller varieties.

With increasing planting density, the root system changed from a framework of mainly horizontal roots with a few vertical sinkers to one of mainly of sinkers, where a much higher proportion of roots were present at depth (Atkinson *et al.* 1976).

Atkinson and Wilson (1979) concluded that the uptake of mineral nutrients was likely to occur over the whole root surface under field conditions and hence a high root surface area was important for the uptake of nutrients such as phosphorus whose diffusion in soil was limited.

Fowkes and Landsberg (1981) were of opinion that a root usually required a large surface area to be an efficient absorber. A root with laterals would be an efficient structure for water absorption and transport only if the laterals were effectively proportioned and the main root itself appropriately structured.

Studies of phosphorus uptake from the soil showed a good relationship for young trees between new root production and absorption. The enhanced phosphorus uptake was attributed to increased root activity. (Atkinson, 1983). Atkinson concluded that the integrated functioning of the whole range of root types was needed for the maintenance and activity of the total root system.

Root systems generally consisted of two parts – 1) fine roots less than 2 mm in diameter and 2) structural roots larger than 2 mm in diameter, which provided the framework supporting the fine roots. Major part of the root system consisted of fine roots in young plants. Vertically, the greatest concentration of fine roots was usually in the top 10cm of mineral soil. The length of fine roots decreased with increasing soil depth (Eis, 1974).

Atkinson (1983) showed that roots of all ages could absorb both water and mineral nutrients, and that new root production could have a large impact on total length available for absorption. Distance from a tree influenced root density and root growth. Root density was found to be highest closer to the tree trunk and usually declined with depth (Roberts, 1976). The decline in root density with distance from a tree, according to Roberts, might be due to the changes in fine root fraction. Rooting density usually increased with age and root spread decreased in relation to height.

2.1.6. Root- shoot inter relationship

The inter relationship between the root and shoot development has been subjected to a detailed study by many workers.

Troughton (1960) made a study on the relationship between shoot and root system of grasses.

Lupton *et al.* (1974) carried out studies on root and shoot growth of semi dwarf and taller winter wheats.

Klepper *et al.* (1984) studied root and shoot development in winter wheats.

The relation of root systems to shoot systems in vascular plants was studied by Groff and Kaplan (1988), and have discussed concepts of root and shoot in the paper. They defined shoot system as the total of all shoots that can trace their origin through other shoots to the same parent shoot. Similarly root system was defined as the total of all roots that could trace their origin, through other roots, to the same parent root.

According to Schulze (1983), it was very difficult to describe a functional root/shoot equilibrium in perennial herbaceous plants because the below ground part served not only for water and nutrient uptake but also as storage. The interactions of water and nutrient flows on carbon relations were explained and typical features of root/shoot ratios in perennial plants and woody species were discussed.

2.2. STUDIES ON ROOTS IN ARECACEAE

Various aspects of roots of palms have been subjected to detailed studies by various workers.

Saakov (1954) noticed two types of germination in palm seeds- admotive and remotive. Mahabale and Nandini shirke (1967) noted that germination was remotive in most palms. Seed germination in the genus *Caryota* was discussed in detail.

Characteristics of palm root system development during the 1st year were discussed by Kozlova (1973). While the root system of the date palm, Washington palm and Chamaerops grew 72-79 cm into the soil and consisted of the primary embryonic root and 1 or 2 secondary roots, root systems of *Trachycarpus* and *Palmetto* grew 10-15 cm only and consisted of 3-6 ramified roots.

The origin of root system in palms have been dealt by Mahabale (1982). He noticed that the number of adventitious roots in reedy palms were much lesser compared to other palms with a big trunk. However in palms like *Calamus*, the roots were few but very strong and stout. According to him, probably the strains and the counterstrains produced by the leaves at the top were balanced by the roots formed in all direction around a palm pole.

In *Areca* (Bavappa and Murthy, 1961) the seed germinated within 30 days after sowing and the root at this stage was about 6 mm long. 2 other roots were produced from the region of the first root. Subsequent roots emerged from the point opposite the site of emergence of the first root. Rootlets of various sizes were formed in about 90 days after sowing. The main roots put forth several lateral branches which again branched forming a root cluster (Davis, 1961). This was similar to what was observed in rattans.

Davis (1961), described the roots of arecanut in relation to their origin, size, shape, function, structure etc. and classified them into 1) adventitious roots emanating from the bole of the root-producing region. 2) the rootlets that branch from the main roots or their branches 3) the pneumatophores or breathing roots and 4) the aerial roots which arise from the aerial parts of the stem. Lakshmana (1993) also reported the presence of negatively geotropic roots or pneumatophores in *C. nagbettai, C. metzianus* and *C. rotang.*

Banik and Ahmed (1986) conducted an investigation on the roots of Barabet (*Calamus viminalis* Willd. var *fasciculatus* Ben). The seedlings were found to produce a well developed seminal root within 10 days of germination. After one month, the lateral roots were found to appear from this system. At the age of 5 months, roots developed from the base of the stem also. Seminal root either stopped growing or degenerated between 6 and 11 months. The root system was of horizontal spreading type.

Evaluation of the distribution pattern of oil palm (*Elaeis guineensis*) root system was done by Alvarado and Sterling (1993).

Nasi (1994) suggested that though root systems of rattans showed a great consistency in their architecture, which was rather simple, it presented also a highly opportunistic behaviour with systematic regeneration of damaged roots. Importance of the proximal bottle- neck created by the root system development was stressed. According to Nasi, allometric relationships established between different parts of a plant showed the peculiar growth strategies of rattans and allowed confirmation of some hypotheses made during the study of the vegetative architecture.

Roots of 36 genera out of 39, coming under Coryphoideae, were distinguished by root characteristics alone. Root anatomy provided a complementary tool to demonstrate both relationships of genera and tribes as well as evolutionary trends within this subfamily (Seubert, 1997).

In modelling and simulation of the architecture and development of the oil-palm (*Elaeis guineensis* Jacq.) root system, estimation of root parameters was done using the RACINES post processor (Jourdan and Rey, 1997).

Dransfield (1997) while dealing with the rattan taxonomy and ecology, information was provided on rattan structure, which included the root system also.

Following a transitional juvenile phase, Jourdan and Rey (1997) distinguished eight different morphological types of roots according to their development pattern and state of differentiation in oil palm. The relative position of these types of roots determined a morphological and functional unit of the root system called the root architectural unit of the oil palm. The root polymorphism made it possible to define a morphogenetic gradient, which reflected the oil palm root system ontogeny.

Fisher *et al.* (1999) noted that roots of *Serenoa repens* had only primary growth and ranged in thickness from 8 mm (First order roots from the stem) to 0.8-2.9 mm (ultimate roots of third to fifth order). The thickest roots occurred at soil depths >20cm and fine roots < 1.2 mm occurred at all depths (1-60 cm). Some second and third order roots were negatively geotropic and grew up to the mineral soil surface.

2.3. ROOT - SOIL INTERACTIONS

Since not much studies were conducted in monocots, relevant references from other groups were also dealt with in this section.

The stresses which roots can experience in soil fall into three broad groups though often interrelated groups. Chemical stresses caused by the shortage of nutrients, their unbalanced supply or by the presence of toxic substances, physical stresses caused by an inadequate water supply, by the mechanical impedance to root penetration, by anaerobic conditions or by unfavourable temperature and biological stresses caused by flora or fauna of the soil. Of these physical and chemical stresses will be discussed in the following paragraphs.

2.3.1. Root growth as influenced by the physical conditions of soil

Wiersum (1961) reported that generally part of the soil was utilized and that a large portion of the soil was not being exploited by the roots. He also concluded that the volume of the soil mainly contributing to the nutrition of the plant in the field was much smaller than the total volume occupied by the roots.

It was noticed by Stevenson (1967) that root and top growth of clover, wheat and sunflower varied consistently and quantitatively with changing soil volumes and he discussed effective soil volume in terms of root growth and root densities. According to Voorhees et al (1971) the penetration of a given soil volume by a root will depend to some extent upon the root anchorage immediately behind the root tip. He added that the extent of secondary root and root hair development were having a large influence on the anchorage of the root.

Jones (1983) studied the effects of soil texture on critical bulk densitites for rooting at near optimum soil water contents and reported highly significant negative relationships between percentage of clay or silt + clay and the bulk density at which rooting was at a maximum. According to him rooting density in the field can vary for a number of reasons including crop species, stage of development, soil water content, nutrient availability and soil strength. Richards and Greacen (1986) found that the rate of elongation of root reduced due to a number of factors, in particular, increased mechanical resistance and decreased internal drainage and aeration. These limiting condition occurred together when the soil was compacted, making it difficult to distinguish unequivocally between their effects. But Krieter (1986) noticed that root development was vigorous even in compacted soil, with deep roots at a distance from the trunk, provided there were adequate macropores present. Pabin *et al.* (1998) concluded that bulk density and soil strength were the two major soil physical factors affecting root growth of pea seedlings. Goodman and Ennos (1999) studied the effect of altering soil strength, i.e. by changing its bulk density, on the morphology and mechanics of the major anchorage roots and, the anchorage strength of sunflower (*Helianthus annuus*) and maize (*Zea mays)* was examined. Penetration resistance was higher in soils with high bulk density than those with low bulk density. Three different experiments under controlled conditions were conducted by Lav-Bhushan *et al.* (1999) to study the effects of depth (0.05, 0.10, 0.15, 0.20, 0.25 and 0.30 m), bulk density (1.36, 1.46, 1.56, 1.66 and 1.76 t/m^3) and aeration status of root zone (with and without drainage of soil) on root growth and yield of wheat. Results showed that root mass increased progressively and significantly with the increase in root-zone depth from 0.05 to 0.30 m, but decreased with the improvement in aeration status of root zone. Shoot growth was also affected significantly by depth, density and aeration status of root zone but not in the same proportion and direction as the root .

Paolillo *et al.* (1999) studied the effects of soil moisture on root growth characteristics of *Citrus* seedlings. They noted that as soil becomes drier, roots become thicker and it may be related to increased lignification of the roots. Root length was found to decrease at lower soil moisture levels.The importance of soil moisture on root growth and development in different crops was also studied by Korikanthmath (1998), *Feng-Guang Long et al.* (1998) and Fu- Hai Qing *et al.* (2000).

Singh and Sainju (1998) reported that in addition to various physical properties, nature of horizon in the soil profile also played an important role in the development of roots. According to them roots of different crop species as well as of cultivars within species differed considerably in their ability to penetrate through hard soil layers.

The pattern of morphological variability of the short roots of Norway spruce (*Picea abies*) growing in different soils was investigated by Ostonen *et al.* (1999). Five root parameters viz., diameter, length and dry weight of the root tip, root density (dry weight per water-saturated volume) and specific root area (absorbing area of dry weight unit), were studied with respect to 11 soil characteristics. Root morphological characteristics most strongly related to the measured soil characteristics in the different sites were specific root area, root density and diameter of the short roots, the means varying from 29 to 42 $m^2 kg^{-1}$, from 310 to 540 kg m^{-3} and from 0.26 to 0.32 mm, respectively; root density being most sensitive. The most favourable site and soil types resulting in fine roots with morphological characteristics for optimizing nutrient uptake (e.g. low short root density and high specific root area) were Umbric Luvisol, Dystric Gleysol and Gleyic Luvisol. These soil types corresponded to highly productive natural forest stands of Norway spruce in Estonia. All measured soil variables explained 28% of total variance of the root characteristics. The most important variables related to root morphology were the humus content, field capacity and specific soil surface area.

2.3.2. Root growth as influenced by the chemical properties of soil

Cornforth (1968) discussed the relationships between soil volume used by roots and nutrient accessibility in Oats, rye grass and tomatoes. He noted that phosphorus uptake was correlated with root intensity while nitrogen uptake was not.

Newman and Andrews (1973) suggested that potassium uptake per unit amount of root was generally lower when the root density was higher suggesting that roots were competing with each other for potassium even at the lowest density. In contrast, phosphorus uptake showed a good correlation with root growth irrespective of root density or plant age. Gahoonia *et al.* (2000) noted that in both laboratory and field experiments, barely *Cv. Salka*, with longer root hairs (average 1.10 mm) absorbed twice more phosphorus from rhizosphere soil than cv. Zitar, with shorter root hairs (average 0.63 mm). Covacevich *et al.* (1998)

based on their investigation on the effects of phosphorus and nitrogen supply on shoot and root growth in wheat (*Triticum aestivum*) have concluded that phosphorus uptake and root length were increased by phosphorus and nitrogen supply and that root shoot ratio decreased with phosphorus addition because of increased shoot growth relative to root.

The bulk of the mineral salts taken up by plants were derived from humus. Nitrogen was needed in large amounts than others. It was noted that a rich supply of nutrients, especially N promoted vigorous branching in roots, but no great extension, so that the root system was found to be more compact than it would be on a poor soil (Willis, 1973). According to him, calcium affected the activities of roots both directly and indirectly. It appeared that the presence of Ca ions in the soil solution antagonised the uptake of phosphate ions. As calcium readily leached out of the soils, stratification was usual, with the surface layers acidic and alkalinity increasing with depth.

Investigations by Reiter *et al.* (1983) on the root systems of healthy and unhealthy silver fir trees at 3 different sites showed no clear differences in pH and exchange properties between soils around healthy and damaged trees in the same study area. Unhealthy tree had shallower root systems with greater fine root numbers and length near the surface than healthy trees which had less fine root complexes. The potassium content of the roots of healthy trees was consistently higher.

Hallmark and Barber (1984) suggested that in soyabean increasing soil P increased root surface area per plant, and root surface area per gram of root. Significant P and K interactions were found for secondary root radius, P, K and Mg influx showing that P and K had their greatest effect when the other nutrient concentration in the soil was high.

Krieter (1986) based on his investigation of the soil under lime trees concluded that root development could be vigorous even in compacted soil, with deep roots at a distance from the trunk, provided there were adequate macropores present.

According to Cavelier (1992) a large root biomass in montane forests was related to nutrients in low concentration and dilution in organic soils with high Cation exchange capacity and low bulk density, and that fine root biomass in tropical forests was inversely related to calcium availability but not to phosphorus as had been suggested for other forests.

The importance of pH on root hair development was stressed by Canmore-Neumann *et al.* (1997) in *Leucadendron* cv. Safari Sunset. The high pH inhibited root growth and subsequent shoot growth. A marked effect of the pH on the proliferation of root hairs was demonstrated by using a scanning electron microscope. In roots of plants grown at high pH, root hair development was arrested, thus decreasing the potential surface area, which might decrease plant nutrient uptake. Safari Sunset required low pH in its rhizosphere for adequate growth, as root hairs developed only at pH lower than 6.

Bojarczuk (1997) based on his studies in birch clone found that aluminium toxicity was the main factor limiting plant growth in acid media. Aluminium at low concentrations (25 mg/litre, pH 5.5) had no inhibitory effect and even stimulated development of shoots and roots, but its presence in media at pH 4.0 resulted in a significant decrease in the growth of birch microcuttings. Aluminium at a higher concentration (100 mg/litre, pH 5.5) inhibited the development of adventitious roots, and reduced the number and length of roots and their fresh and dry mass.

An overview of the effects of elemental toxicity (Al, Cd, Ni, Pb, Cu, Mn and Zn), deficiency (N, P, K, Ca, Mg and trace elements), low soil pH and salinity on root growth and morphology in field and horticultural crops had been reported by Baligar *et al.* (1998).

The effect of aluminium (Al) and phosphorus (P) on root hair growth of Al-tolerant and Al-susceptible white clover genotypes was investigated by Care and Box (1996) by growing stolen tips of each genotype in a low ionic strength hydroponic culture. There were significant differences between the Al-tolerant and the Al-susceptible genotypes for total root hair length per plant and root hair number per plant. Aluminium significantly reduced total root hair length per plant and root hair number per plant. Phosphate significantly affected the response of total root hair length per plant to Al. Hirano and Hijii (1998) reported the effects of low pH or excess Al on the root morphology and nutritional status of 2-yr-old Japanese red cedar (*Cryptomeria japonica*) saplings. The results revealed that the root morphology of the saplings was adversely influenced not by low pH but by excess Al in brown forest soil, indicating that this type of soil might have the potential for producing a decline in the root systems of Japanese red cedar. The effects of excess Al were characterized by an increase of root diameter and an increased concentration of P and Al in the white roots. According to Clune and Copeland (1999) at concentrations of Al >60 æM, root growth of *Brassica napus* var.*napus* L. was strongly inhibited, with cellular damage being observed primarily in peripheral root cap cells.

Mac Donald (1997) observed in *Bixa orellana* that soil with higher fertility had higher dry matter yield and greater production of roots. Nitrogen levels in the rooting medium influenced root production more than did K and P. However, N, K and P had no influence on the elongation of the tap root.

Luo-HuiMing *et al.* (1999) suggested that the exudation of citric acid might contribute to the detoxification of Al and to the increased phosphate availability in the rhizosphere in rape. Gottlein *et al.* (1999) based on his studies had shown that while the concentrations of nutrient cations, especially Ca^{2+} and Mg^{2+} decreased in the vicinity of growing shoots, the concentrations of Al^{3+} significantly increased. Al^{3+} ions were released when root exuded protons were buffered by the soil. They concluded that the oak roots had only limited capabilities to detoxify Al in their rhizosphere.

Nardi and Concheri (2000) conducted a study to investigate mechanism by which root exudates of forest trees ((*Picea abies* and *Pinus sylvestris*) and a crop plant (*Zea mays*) disaggregate and mobilize organic and/or humic fractions from three different forest soils sampled from Cortina d'Amperro, N. Italy. The results indicated that root exudates in forest soils played a very important role at the rhizosphere level and that the novel experimental system was suitable for studying the natural interaction between roots and soil.

Nadelhoffer *et al.*(2000) reported that increases in fine-root turnover and production in forest ecosystem could eventually decrease if chronically elevated N deposition lead to forest stand mortality.

3. MATERIALS AND METHODS

3.1 STUDY AREA

The study was conducted at Kerala Forest Research Institute (KFRI), Peechi, Kerala. The field trials were carried out in the campus of the field research station of KFRI at Veluppadam in Palappilly range of Chalakudy Forest Division (Fig. 1). It occupies an area of 47.43 ha. The area selected for the study was more or less undulating, which receives an average annual rain fall of 4320 cm.

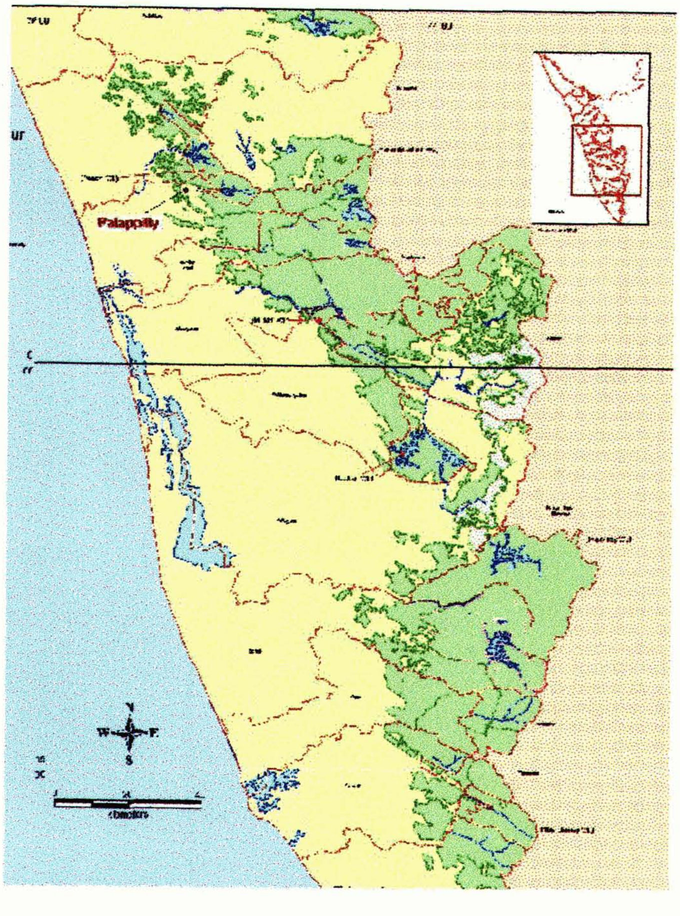


Fig. 1 Study area

Chapter 3.

MATERIALS AND METHODS

3.2. MATERIALS

The two commercially important rattans, *C. thwaitesii* and *C. rotang* were selected for the study. Of these, *C. thwaitesii* is a large diameter cane reaching 3 cm in diameter and *C. rotang* is a small diameter one often less than 1 cm in diameter.

3.2.1. Description of the species

***Calamus rotang* Linn.** A slender, clustering cane. Stem 10 m long or more, with sheaths upto 1.3 cm in diameter, without sheaths to 1 cm, internodes 35-45 cm long. Leaves upto 80 cm long; leaf sheath green, spiny; spines upto 1 cm long, needle like, yellow; knee-prominent; petiole absent; leaflets many, regularly placed, each 24-36 cm x 1.8 –2 cm, upper leaflets gradually becoming smaller, linear lanceolate, margins setulose to spinose, mid-vein ciliate or setose beneath from center upwards (Fig. 2) Inflorescence about 3 m long; partial inforescence upto 70 cm long. Fruit ovoid, scales arranged in 21 rows, faintly channelled along the middle and straw yellow coloured.

Distribution

This species is restricted to the plains along the coastal regions and backwaters, usually seen in the sacred groves at 50 m elevation and coastal regions of Alappuzha and Kollam districts. It is reported from Sri Lanka also.

Flowering : October – December

Fruiting : March – May

***Calamus thwaitesii* Becc. & Hook.f.** A very robust, clump forming, large diameter rattan. Stem with sheaths to 6 cm in diameter and without sheaths to 3.5 cm. Leaves about 3 m long; leaf sheath yellow, densely armed with black spines, arising from a raised rim-like surface, the largest 3 x 0.7 cm, flat, smaller spines scattered in between; knee absent; petiole and rachis yellowish, armed with black spines which are grouped and arranged into oblique whorls; leaflets usually grouped, sharply spinulose along the margins (Fig. 3). Inflorescence about 6 m long, partial inflorescence about 70 cm long. Fruit about 2 x 1.3 cm, ovoid, scales arranged in 12 vertical rows with median grooves, yellow with deep brown margins.

Distribution

This species grows in evergreen, semi evergreen and moist deciduous forests between 75 to 900 m elevation through out the Western Ghat. The distribution extends to Sri Lanka also.

Flowering : July - August

Fruiting : April – May

The root system of *Calamus* is fibrous, which is a typical character of monocolyledons. The radicle develops into fibrous root system. Later roots develop from the base of the stem. Roots generally spread to a width of 1-2m and to a depth of 50-60 cm. Small and tender species have a smaller distribution of the root system while robust canes have a wider and deeper distribution. There is a positive relation between spread of the root system and growth of the plant. Roots may either grow geotropically or apogeotropically (Dransfield, 1979b). The apogeotropic roots may be concentrated in the leaf litter layer and frequently bear patches of loose corky tissue, usually associated with gas exchange.

Fig. 2. *Calamus rotang* Linn.

Fig. 3. *Calamus thwaitesii* Becc. & Hook.f.

Habit

The root system holds the plant firmly in the ground and absorbs nutrients from the soil. The roots hold the soil firmly and prevent erosion. The rhizomatous roots also help in multiplication and spreading of the parent plants.

3.3 METHODOLOGY

Mature fruits of *C. rotang* and *C. thwaitesii* were depulped and put to germination in moist sawdust. The method of germination was observed. The germinated seeds were used for further field trials.

3.3.1 Root morphological studies

The experiment was laid out in a randomized complete block design with two species replicated five times. Thus 900 seeds of each species were planted. The plot size was (90 m x 4.5 m) with plants at an espacement of 1.5 m x 1.5 m. Thus, in each plot, there were three rows of 180 germinated seeds with 60 seeds in a raw. Alternate plants from the central row were selected for recording observations, leaving all the plants in the other two rows, to maintain uniform growing conditions through out the observation period. Initial growth measurements of the root system of the germinated seedlings were made after 2 months. Later on, measurements were taken for both species at an interval of 2 months for 3 years. Thus 18 x 5 observations were recorded for each species. For biomass studies observations were taken on an yearly basis. Here also plants were selected from the central row as described earlier. For soil studies also plants were selected similarly.

The main problem in studying the behaviour of roots in nature is that it is impossible to observe a root growing in soil. Most of the studies are conducted in water culture and other artificial media or through rhizotrons, where the behaviour of roots, although easily observed, may have little bearing on their actual behaviour in soil. Hence for recording observations with respect to the morphology of root system, excavation of the entire root system was carried out, since this method could provide a clear picture of the entire root system of a plant as it exists naturally. Excavation was done by taking care not to damage even the smallest root let. Soil around each root was removed carefully and slowly after sprinkling adequate water. Before taking the plant out of soil, horizontal and vertical distances the roots had traversed were measured. After taking out, the roots were washed carefully with water to remove all the soil particles. The number, length and diameter of all the main roots and laterals were measured. Here, the first formed root and other roots emerging from the base of the plant are called as main roots. The branches of these roots are called as laterals and branches from them are referred to as sublaterals (Fig. 4).

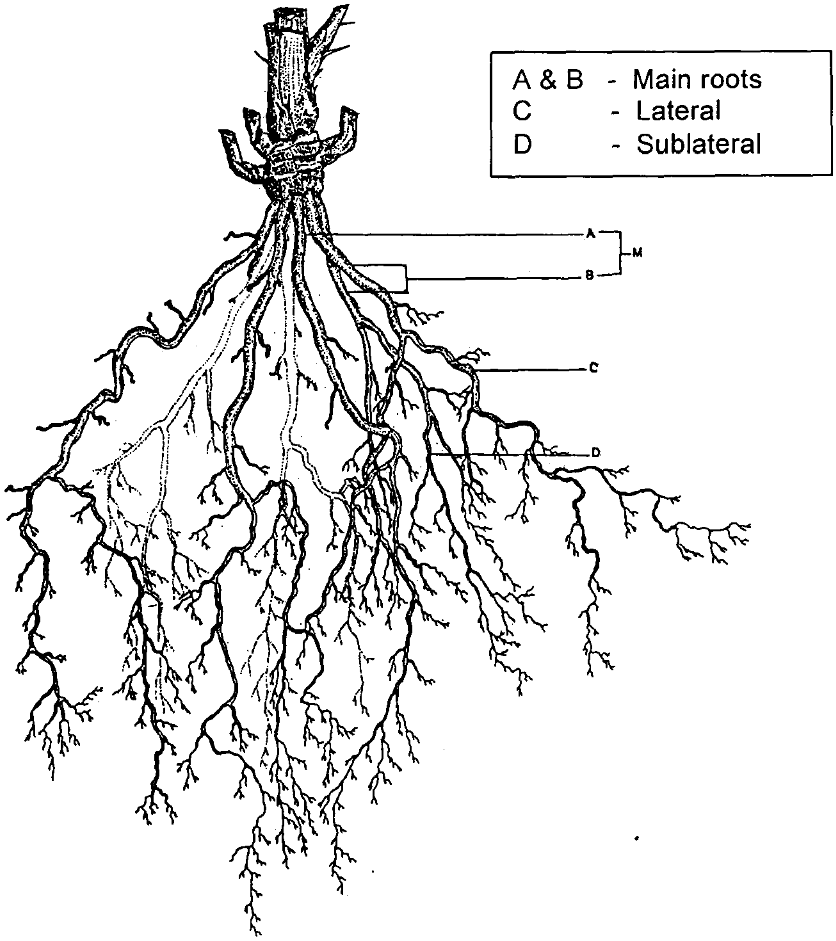


Fig. 4 General root morphology

3.3.1.1 Growth characters

Number

Number of main roots, laterals arising from the main roots and also sublaterals emerging from the laterals were counted. Number of root lets arising from these main roots and laterals also were recorded. The data were subjected to Analysis of variance in order to find variation in number of roots between the two species.

Length

The length of the roots was measured using a scale and a thread. The thread was placed from the emerging point of the root till its tip. The measured thread was then placed on a scale and the length noted. The data with respect to the length of main roots, laterals and sublaterals were also subjected to analysis of variance so as to find the variation in length between the two species and was followed by comparison of their mean values. Rate of increase in length of main roots, laterals and sublaterals of the two species in each year (from second year onwards) was calculated using the formula $\frac{l_2 - l_1}{l_1}$ where l_2 is the average length of the main/lateral/sub lateral root in a particular year, and l_1 the average length of main/lateral/sublateral root in the previous year.

Regression functions were fitted for two species separately for mean total length of root to study the pattern of changes in the above character with the period.

Diameter

The diameters of main and lateral roots were measured using vernier calipers. Diameter of sublateral roots was measured using an ocular micrometer. In order to find variation in the diameter of roots between the two species, the data was subjected to analysis of variance followed by comparison of their mean values. Rate of increase in diameter of main roots, laterals and sublaterals of the two species in each year (from second year onwards) was calculated using the formula $\frac{d_2 - d_1}{d_1}$ where d_2 is the average diameter of the main/lateral/sublateral root in a particular year, and d_1 the average diameter of main/lateral/sublateral root in the previous year.

Regression functions were fitted for two species separately for mean diameter of root to study the pattern of changes in the above character with the period.

3.3.1.2 Root spread

Maximum horizontal distance, traversed by the root system of plants was measured with the help of a metre scale. For this, before taking the plant out of the soil, distance between the two outer most roots was measured. Vertical soil depth occupied by each of the main roots was also measured using a metre scale. In order to find out the variations in horizontal spread and vertical depth of the root system between species, the data were subjected to analysis of variance. This was followed by comparison of their mean values.

3.3.1.3 Soil volume exploited

Soil volume exploited by the root system of plants for the two species of *Calamus* was calculated on an yearly basis using the formula $\pi\left(\frac{h}{2}\right)^2 v$, where '*h*' is the mean horizontal spread of the root system in each year obtained from the data collected at two months interval and '*v*' is the mean vertical depth of the roots. The two species were compared based on the soil exploited by their root system.

3.3.1.4 Effective soil volume

Effective soil volume for the two species in each year was calculated from the graph drawn by plotting exploited soil volume against rooting density for each period separately. It is that soil volume at which rooting density shows a sharp decline. The effective soil volume calculated for each of the species year wise was compared.

3.3.1.5 Rooting density

Rooting density of each of the *Calamus* species was calculated separately on yearly basis applying the formula $\frac{R_{max}}{s}$, where 'R_{max}' is the total length of the main roots, laterals and sublaterals and 's', the soil volume exploited by the entire root system. Rooting density was also calculated making use of the data with respect to core samples taken at the end of third year. The results obtained for two species were compared.

3.3.1.6 Root intensity

Root intensity of each species was calculated from the total number of roots present in unit area of the soil. It was calculated from the data with respect to core samples taken at the end of third year. Percentage root intensity contributed by the fine roots less than 2 mm diameter was also calculated in each of the species by considering the number of fine roots alone. A comparison was made between the two species based on the results obtained.

3.3.1.7 Root surface area

Root surface area was calculated separately for roots less than 2 mm diameter and greater than or equal to 2 mm diameter, using the formula $2\pi rl$ where 'r' is the radius of roots and 'l', their length. Root surface area per plant calculated for each year in the two species was compared.

3.3.1.8 Soil binding capacity

Soil binding capacity for the laterals and sublaterals were separately found out using the formula $\frac{v}{r^2}$ where 'v' is the average root volume obtained over plants observed and 'r' the mean radius of the roots of the plants. The root volume was found out using the formula $\pi r^2 l$ where '*r*' stands for mean radius of the laterals/sublaterals roots of the plants considered for the study and '*l*' their mean length. The results obtained for the two species were also compared.

3.3.1.9 Biomass

The root system was separated from the shoot system and both were weighed separately to get their fresh weight. They were dried in an oven and the dry weights were recorded.

Shoot - root relationship with respect to fresh and dry weight of each of the two species for different periods was calculated. In order to compare the two species with respect to shoot- root ratio of fresh and dry weight, the Student's t - test was carried out with respect to fresh and dry weight separately for the different periods.

3.3.2 Relation between root growth and soil characteristics

Growth of the plant, especially the underground part is controlled mainly by the type of soil in which it grows. Depending upon the physical and chemical properties of soil, the growth and development of root system differ. Here, in this section, methods followed to estimate the various physical and chemical properties of the soil and their relation to root growth of *Calamus* species are described

3.3.2.1 Soil sampling

For collecting soil samples, 5 plants from each species were selected from the central row as described earlier. Soil samples were collected using a 4 cm diameter core from four different depths (0 – 15 cm, 15 – 30 cm, 30 – 45 cm and 40 – 60 cm) at 0, 10 and 30 cm away from the base of the plant. There were 3 randomly selected sampling points around a single plant in order to get fragments of the roots, which spread, in all directions. Thus there were a total of 28 samples from a single plant (12 at 10 cm from the base, 12 at 30 cm away from the base and 4 immediately from below the base of the plant) and thus there were 140 samples from 5 plants for each species. Separate soil samples (@ 28 per plant) were also collected for estimating soil moisture content.

3.3.2.2 Processing of soil samples

The soil samples, brought directly from the field, were air dried in the shade for 4 – 5 days and were weighed. Root fragments were separated from each sample and used for root determining the different root parameters such as root length, total root weight, fine root weight and rooting density. Soil was then sieved through a 2 mm sieve and gravel content was accounted. The 2 mm sieved soil samples were used for soil analyses.

3.3.2.3 Analytical procedure

Physical properties

Soil moisture was estimated using gravimetric method. Important physical properties like texture (international pipette method) and bulk density (core method) were estimated following the procedures described by Black *et al.* (1965a).

Chemical properties

The pH of soil water suspension (1 : 2.5) was determined using a digital type Elico pH meter.

Organic carbon content was estimated by sulphuric acid and potassium dichromate acid digestion (Walkley and Black, 1934) as described by Jackson (1958).

Available N was estimated by alkaline permanganate method (Subbiah and Asija, 1956). Available P was extracted by Bray No.1 extractant (0.03 *N* NH_4 F + 0.025 *N* HCl soil solution ratio 1:10; period of extraction 5 minutes) and the P content was determined colorimetrically by the ascorbic acid reduced molybdophosphoric blue colour method in hydrochloric acid systems (Watanabe and Olsen, 1965) using Spectronic Unicam Spectrophotometer.

Exchange acidity of the soil was estimated by titrating 1 *N* KCl extract of soil (soil solution ratio 1 : 5; period of extraction 30 minutes) with standard NaOH using phenolphthalein as indicator (Yuan, 1959).

Exchangeable Al was estimated by titrating 1*N* KCl extract of soil followed by 0.05 *N* HCl (Black *et al.* 1965b).

Exchangeable K, Na, Ca and Mg were estimated from the neutral ammonium acetate extract of the soil. Five gram of soil was extracted with neutral normal ammonium acetate 1:15 for 10 minutes, filtered and the filtrate was used to determine K and Na using a digital type Elico (CL -361) Flame Photometer (Jackson, 1958). The same filtrate was used to estimate Ca and Mg using complexometric EDTA titration (Hesse, 1971).

In order to know the influence of radial distance and soil depth on root parameters, mean values of these at different depths and radial distances were compared. Correlation coefficients between soil properties and root parameters were determined for each species.

Response functions were fitted relating the fine root weight and rooting density to different soil variables separately for each species.

3.3.2.4 Determination of root parameters

Root Weight

The root fragments separated from the soil samples were weighed to obtain total root weight. They were then sieved through a 2 mm sieve to get the fine roots, which were also weighed to obtain the fine root weight.

Root Length

Length of all the roots in the samples was estimated using Newman's line intersection method. For this a transparent plastic trough was placed over a 1 cm^2 graph paper. Root fragments of each soil sample along with a certain amount of water was then poured into the trough. These were then arranged in such a manner that they do not touch one another. Since the lines of the graph paper are visible through the transparent trough, Number of intersections of the root pieces with the horizontal and vertical lines on the graph paper could be counted. Root length was calculated using the formula $R = \frac{11}{14}N$, where '*N*' comprise all intercepts of roots with total length of vertical and horizontal grid lines. '*R*' is measured in terms of grid units.

Rooting Density

Rooting density in each soil sample was calculated from the root length using the formula $\frac{l}{v}$ where 'l' is the total root length in each sample and 'v' is the volume of the soil present in that core sample.

4. OBSERVATIONS

4.1 Root morphology

Seeds of *C.rotang* and C. *thwaitesii* were found to germinate one month after sowing. The mode of seed germination and the nature of origin of roots in *C. rotang* and *C. thwaitesii* were similar. The first structure to emerge from the germinating seed was a white columnar plug. As the plug got elongated, plumule emerged from one side. After 2 - 3 days, radicle developed on the opposite side of the plumule (Fig. 5.).As the plumule gradually turned green in colour, the radicle remained white. It becomes the primary root of the seedling. The primary root was provided with a root cap. Numerous rootlets were produced from the primary root (Fig. 6). Lateral roots emerged from this root within 2 – 3 weeks and this root system remained functional for about 2 months. The seed remained attached to the plant through out this period (Fig. 7).

Measurements of the root system of the germinated seedlings were made after 2 months initially. Later on, measurements were taken for both species at an interval of 2 months.

After 2 months

C. rotang developed two roots at this stage, each root reaching more or less a length of 10.68 cm. Average thickness of these roots was 0.88 mm. Number of rootlets developing from the roots of a plant at this stage was about 43. Average depth of the soil occupied by the roots was 9.94 cm.

C. thwaitesii developed single root at this stage. Length of this root was 14.39 cm. Thickness of the root was 1.18 mm and average number of root lets developed from the roots of a single plant was 46. Depth of the soil occupied by the root was 11cm.

Even though *C. thwaitesii* was found to show lesser number of main roots, the roots of this species was found to attain more length and thickness and develop more number

Fig. 5. Emergence of radicle

Fig. 6. Development of primary root

Different stages of seed germination in *Calamus*

Fig. 7. Primary root with root lets

of rootlets compared to that of *C. rotang*. Since the main roots emerging were found to be closer to each other, distance between these roots have not been measured during the initial stages so that the horizontal spread of the root system has not been recorded.

After 4 months

In *C. rotang*, three roots were found to develop at this stage. The roots having an average length of 10.93 cm. Average thickness of these roots was 0.91 mm. About 67 rootlets developed from the roots of the plant. The roots occupied an average soil depth of 10.13cm

two main roots developed at this stage in *C. thwaitesii*, the roots reaching an average length of 17.13 cm, and an average thickness of 1.52 mm. The roots reached a soil depth of 27.50 cm and developed about 60 rootlets. Lateral roots emerged from the main roots at this stage. The 2 lateral roots developing from the main roots had an average length of 13.76 cm and thickness of 1.45 mm. A total of 31 rootlets developed from the secondary lateral roots.

Number of main roots in *C. thwaitesii* at this stage was found to be lesser than that of *C. rotang*. However, the length, thickness and the soil depth occupied by the roots in *C. thwaitesii* exceeded that of *C. rotang*. the number of rootlets from the main roots was found to be more in *C. rotang.* Initiation of lateral roots at this stage was seen only in *C. thwaitesii.*

After 6 months

C. rotang developed four main roots, reaching an average length of 11.17 cm. Thickness of the roots was about 0.91mm. Number of rootlets at this stage increased to 73. The roots with and <1.3 cm length did not develop rootlets. Depth of the soil occupied by the roots was 11.62 cm. Maximum horizontal distance between the two peripheral roots was 5.20cm. An average of 2 laterals were found to originate from the main roots, their length reaching 7.49 cm. Laterals developed rootlets, their number reaching upto 26 (Fig. 8).

C. *thwaitesii* developed three main roots on an average having 11 -12 cm length. Thickness of the roots was 1.15 mm. Most of the roots showed the presence of rootlets. However, main roots with a length of 3.2 cm and below it were devoid of root lets. The number of rootlets on an average was 49. Maximum horizontal distance between the two peripheral roots was 4.6 cm. Depth of the soil occupied by the roots on an average was 11.94 cm (Fig. 9.).

The number of main roots developed by the seedlings, their length and thickness were more or less the same. Number of rootlets was markedly more in *C. rotang*. However, a slight increase in the vertical growth of the root system was seen in *C. thwaitesii* while more horizontal spread was found in *C. rotang* at this stage. No laterals were produced in roots of *C. thwaitesii* at this stage.

After 8 months

C. rotang developed five main roots, having an average length of 10.58 cm. Thickness of the roots was 0.90 mm. Most of the roots showed the presence of rootlets. Roots of 2cm length and lesser than that were devoid of rootlets. Average number of rootlets produced per plant was 103. Depth of the soil occupied by the roots was 10.85 cm. Maximum distance between the two peripheral roots was 8 cm. When present, laterals were found to be emerging from one of the main roots in each plant. Number of laterals on an average was 2, their length being 6.20 cm on an average and the number of rootlets being 19 per plant .

In *C. thwaitesii* number of roots developed by the plant was three having 15.07 cm length. Thickness of the roots was about 1.67 mm. All the roots showed the presence of rootlets, their number on an average being 71. Depth of the soil occupied by the roots was 15.36 cm. Horizontal distance between the two peripheral roots was 7 cm. Laterals, when present on an average was 4 in number, having a length of 7.67 cm, the number of lateral rootlets in a plant being 38.

Even though the number of main roots in *C. rotang* was more, they were shorter and thinner when compared to *C. thwaitesii*. However number of rootlets was found to be much more in comparison to *C. thwaitesii*. The horizontal spread of the 2 species was more or less the same, but the soil depth occupied by the roots was far more in *C. thwaitesii* than in *C. rotang*. Number of laterals and root lets arising from these in *C. thwaitesii* was double that of *C. rotang*. Length of the laterals also was found to be slightly more in *C. thwaitesii*.

After 10 months

C. rotang developed five roots at this stage having an average of 11.13 cm length. Thickness of the roots was 1.11mm. All the roots except those which were 2cm and lesser than it were provided with rootlets. Main rootlets arising from a single plant was 76. Depth of the soil occupied by the roots on an average was 11.4 cm. Maximum horizontal distance between the two peripheral roots was 7.18 cm. Laterals were not found to originate from the main roots which were less than 2 cm length. Number of laterals from a single plant on an average was 12. Length of the laterals was 4.5 cm and thickness 0.01 mm. Number of rootlets arising from the lateral roots of a single plant was 79. Almost all the laterals were found to be provided with rootlets.

C. thwaitesii developed three roots at this stage. Their length on an average was 14.46 cm. Thickness of the roots was 1.45 mm. Number of rootlets arising per plant was 56. Depth of the soil occupied by the roots on an average was 14.23 cm. Maximum horizontal distance between the two peripheral roots was more or less 7.4 cm. Number of laterals was 60, their length being 5.61 cm. Number of root lets on the laterals of a plant on an average was 54.

Number of main roots emerging from the plant was found to be more in *C. rotang* than in *C. thwaitesii*. Thickness of the roots was more in *C. thwaitesii* than in *C.rotang*. Depth of the soil occupied by the roots was found to be more in *C. thwaitesii*. The horizontal spread of root system in both species was found to be more or les the same. Number and length of the laterals and the number of rootlets arising from the laterals were found to be almost the same in both the species.

After 12 months

In *C. rotang* number of main roots developed from the plant was six, their length on an average being 15.22 cm and thickness, 1.07mm.The roots greater than 2 cm length were found to have rootlets on them. Number of rootlets present on the roots of a single plant increased to 169.Depth of the soil occupied by the roots on an average was 14.73 cm. Maximum horizontal distance traversed by the root system was more or less 11.10 cm. Laterals were not found to develop from the roots which are less than 5 cm length. Number of lateral roots emerging from a main root was 13, their length being 4.76 cm. Number of rootlets produced from the laterals of a single plant on an average was 116 (Fig. 10.).

In *C. thwaitesii* number of main roots developed was four, their length on an average being 12.89 cm and thickness being 1.33 mm. Roots lesser than 2 cm length were not found to produce rootlets on them. Rootlets produced from the main roots of a single plant were 73. Depth of the soil occupied by the roots on an average was 13.03 cm. Maximum horizontal distance traversed by the root system was 8 cm. Laterals were not produced from main roots lesser than 10 cm length. Number of lateral roots emerging from the main roots of a single plant was 7, their length being 7.31 cm and thickness, 0.04 mm. Number of rootlets arising from the laterals in a single plant was more or less 139 (Fig. 11.).

Number of roots developed and the length attained was found to be more in *C. rotang* than in *C. thwaitesii*. Thickness of the root was found to be more or less the same.

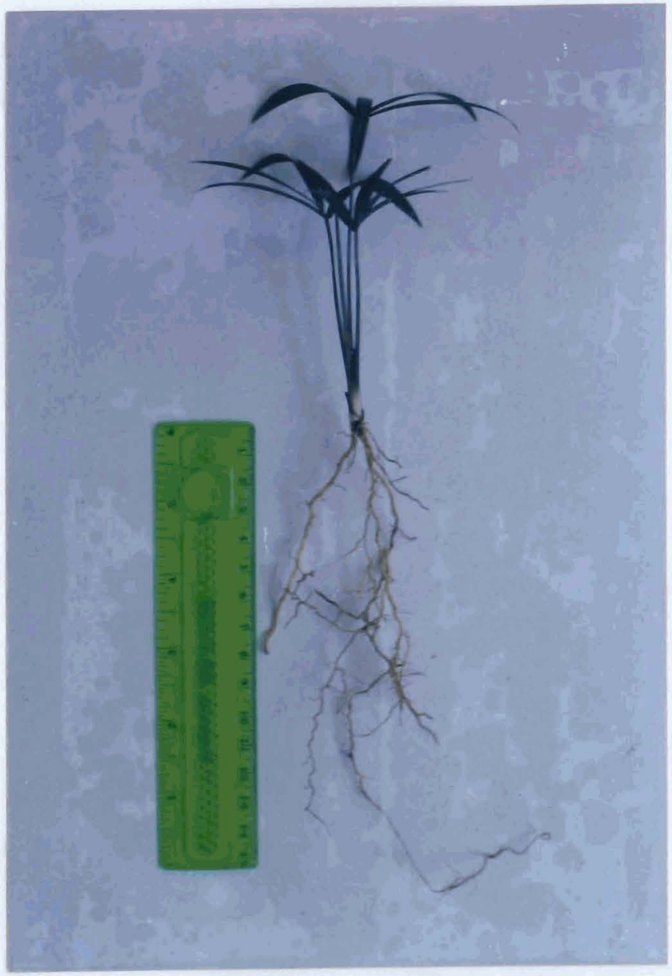


Fig. 8 *C. rotang (6 months)*

Fig. 9 *C. thwaitesii (6 months)*

Root system of *Calamus* at different stages of growth

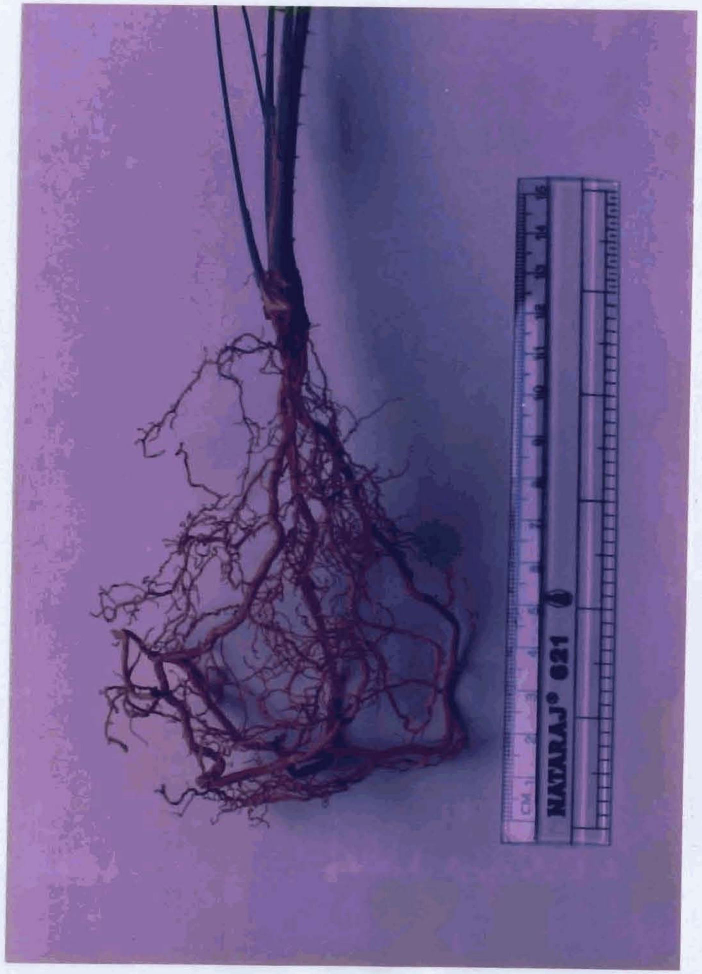


Fig. 10 *C. rotang* (12 months)

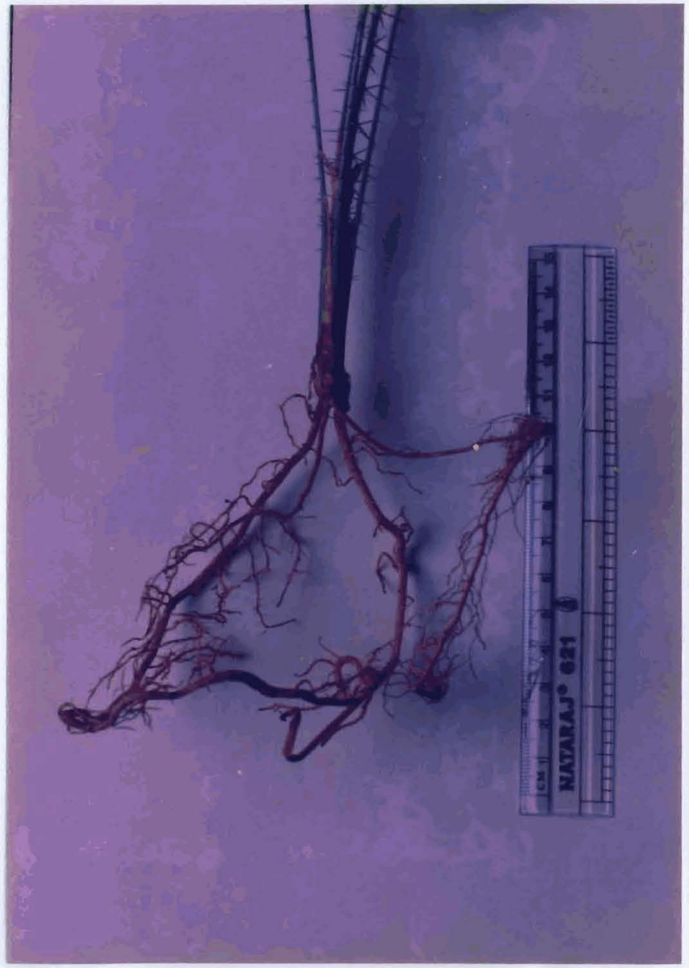


Fig. 11 *C. thwaitesii* (12 months)

Root system of *Calamus* at different stages of growth

However, number of rootlets arising from the main root was found to be markedly more in *C. rotang.* Depth of the soil occupied by the roots and horizontal distance traversed by the root system was slightly more in *C. rotang* when compared to *C. thwaitesii.* Roots were not found to be so close to each other in *C. rotang* as in *C. thwaitesii.* Laterals were not produced from main roots lesser than 5 cm length in *C. rotang* and 10cm in *C. thwaitesii.* Number of laterals produced from the main root of a plant in *C. rotang* was more than that in *C. thwaitesii.* However, the length and thickness of laterals were more in *C. thwaitesii.* The number of lateral root lets from a single plant was also more in *C. thwaitesii.*

After 14 months

C. rotang developed five main roots at this stage. Length of these roots on an average was 13.39 cm, thickness 1.28 mm and the number of rootlets from a plant, 106. Almost all the main roots had produced rootlets. Depth of the soil occupied by the roots from the surface was 13.01 cm, and maximum horizontal distance tranversed by the root system was 9.26 cm. Roots which were lesser than 6.5 cm in length did not produce any laterals. Number of laterals from main root on an average was 9. Length of these laterals was 5.56 cm, and thickness, 25 mm. Average number of rootlets from the laterals of a plant was 87.

C. thwaitesii developed five main roots at this stage. Length of the roots on an average was 16.40 cm and thickness 1.64 mm. Rootlets developing from the main roots of a single plant was 120 on an average. All the main roots developed root lets. Depth of the soil occupied by the roots from the surface was 15.01cm. Maximum horizontal distance traversed by the root system was 12.5 cm. Number of laterals produced from the main roots was seven. Length of these laterals on an average was 4.76 cm and thickness 1.19mm. Almost all the laterals developed rootlets and their number in a single plant was 77.

Number of main roots developed by the two species at this stage was more or less the same. Length of these roots, their thickness and the number of rootlets arising from *C. thwaitesii* were found to be greater than that of *C. rotang*. Almost all the roots produced rootlets in both the species. Depth of the soil occupied by the roots from the soil surface and horizontal spread were found to be more in *C. thwaitesii.* Number of laterals produced, their length and the number of rootlets arising from the laterals of a single plant were found to be little more in *C. rotang* when compared to that of *C. thwaitesii.*

After 16 months

C. rotang developed six main roots at this stage. Length of the roots on an average was 14.49 cm and thickness, 1.16 mm. and the number of rootlets in a plant was 160. Roots with length less than 2 cm did not produce rootlets. Soil depth occupied by the roots from the surface was 14.85 cm. The maximum horizontal distance traversed by the root system was 11.80cm. Laterals produced from the roots were 3 in number, their length being 5.48cm and thickness, 0.41mm. The rootlets produced from the lateral roots of a plant decreased to 22. Lateral roots lesser than 4 cm length did not develop any rootlets at all.

C. thwaitesii developed five main roots at this stage. Roots showed an average of 28.73 cm length and 1.43 mm thickness. Number of rootlets in a single plant increased to 200. Depth of the soil occupied by the roots from the surface was 26.07 cm. The maximum horizontal distance traversed by the root system was 17.6 cm. Laterals produced from the main roots was on an average 12, their length being 8.66cm and thickness 0.40 mm. Number of rootlets from laterals of a single plant was 83.

Number of main roots developed in the two species was almost the same. Length of the main roots, thickness of the roots and number of rootlets were found to be more in *C. thwaitesii* than in *C. rotang*. Soil depth occupied by the root system and the maximum horizontal distance traversed by the root system was also more in *C. thwaitesii* than in *C. rotang*. Laterals produced from the main roots were more in *C. thwaitesii*. Thickness of the laterals was more or less the same in both the species. Number of lateral rootlets developed in a plant was however more in *C. thwaitesii* than in *C. rotang*.

After 18 months

In *C. rotang* eight main roots were developed. Length of the roots was 14.79 cm and their thickness 1.45 mm. Roots lesser than 2.5 cm length did not produce rootlets. All others produced rootlets and their number present in a single plant was 223. Depth of the soil occupied by the roots from the soil surface was on an average 15.99 cm. Maximum horizontal distance traversed by the root system was 11.86 cm. Some of the main roots alone produced lateral roots. Number of lateral roots arising from main root on an average was 7. Their length measured 4.25 cm and thickness, 0.20mm. Number of lateral rootlets in a single plant was 45.

In *C. thwaitesii* five main roots were developed. Length of the roots on an average was 16.60 cm and thickness 1.31mm. Almost all the roots produced rootlets. Number of rootlets from the main roots of a single plant decreased to 136. Depth of the soil occupied by the roots from the surface was 17.41 cm. Maximum horizontal distance traversed by the root system was 10.4cm. Laterals produced from a main root on an average was 4 in number. Their length was 9.53 cm, thickness 0.48 mm and the number of lateral rootlets developing from a plant was 85.

The number of main roots developed by the plant was more in *C. rotang* compared to that of *C. thwaitesii* but the length of these roots were more in *C. thwaitesii*. Their thickness and total number of rootlets per plant were however more in *C. rotang*. Soil depth occupied by roots was more in *C. thwaitesii* while the horizontal spread of the root system was more in *C. rotang*. Number of laterals produced from the main roots was found to be slightly more in *C. rotang*. Their length, thickness and the number of rootlets arising per plant were also found to be greater in *C. thwaitesii.*

After 20 months

In *C. rotang* six main roots were developed. Length of the roots on an average was 18.55 cm and their thickness 1.43 mm. All the main roots had produced rootlets, their number per plant being 186. Depth of the soil occupied by the roots from the surface was 17.95 cm. Maximum horizontal distance between the 2 peripheral roots on an average was 14.30 cm. Roots less than 5.5cm in length did not produce any laterals. Number of laterals arising from a main root was 10. Their length on an average was 5.13 cm and thickness 0.37mm. Number of lateral rootlets produced per plant was 95.

In *C. thwaitesii* four main roots were developed. Length of these roots on an average was 13.42 cm and thickness 1.26 mm. All the main roots showed presence of rootlets. Number of main rootlets per plant was 84. Depth of soil occupied by the roots from the surface was more or less 13.49 cm. Maximum horizontal distance traversed by the roots was 11.24 cm. Number of laterals produced from each of the main roots on an average was 5. They showed a length of 7.37 cm and a thickness of 0.49 mm. Number of rootlets from the laterals per plant was 97.

C. rotang showed more number of main roots when compared with that of *C. thwaitesii.* C *rotang* showed more length and thickness for the main roots and these roots also produced more rootlets. More .soil was occupied by the roots of *C. rotang* than that of C. *thwaitesii.* Maximum horizontal distance traversed by the roots also was more in *C. rotang* when compared with that of *C. thwaitesii.*

Number of lateral roots arising from the main roots was more in *C. rotang* than in *C. thwaitesii.* Length and thicknes of the laterals were found to be more in *C. thwaitesii.* However, number of rootlets arising from the laterals were found to be more or less the same in both the species.

After 22 months

In *C. rotang* eight main roots were developed. Length of the roots on an average was 22.11 cm and thickness 1.89 mm. There were 3 main roots which were lesser than 2.5 cm length out of which one alone produced rootlets. All the other roots greater than 2.5 cm length produced rootlets. Number of rootlets per plant was 168. Depth of the soil occupied by the roots on an average was 17.43cm. Maximum horizontal distance traversed by the root system was 17.70 cm. Some of the main roots alone produced lateral roots. However, one plant with 11main roots produced laterals from 10 of them. Number of laterals arising from the main root on an average was 19. Their average length was 9.78 cm and thickness, 1.04 mm. Number of rootlets arising from these laterals were 181. The number of sub laterals produced on an average was 9. They showed a length of 5.30 cm and thickness of 0.85 mm. The number of rootlets from the sub laterals per plant was 54.

In *C. thwaitesii* six main roots were developed. Length of the roots on an average was 28.47 cm, thickness 2.12 mm. Number of rootlets arising from the roots per plant was 243. All the main roots produced laterals. Depth of the soil occupied by the roots from the soil surface was more or less 26.07 cm. Maximum horizontal distance traversed by the root system was 18.5 cm. Main roots lesser than 5.5 cm length did not produce laterals at all. Number of laterals arising from the main roots on an average was 13 with a length of 5.69 cm and thickness 0.62 mm. Rootlets arising from these laterals were 120 in number. No sub laterals were seen to be produced from any of laterals.

C. rotang showed more number of main roots when compared with that of *C. thwaitesii*. Length and thickness attained by the main roots of *C. thwaitesii* was far more than that of *C. rotang*. The number of rootlets produced from the main roots were more in *C. thwaitesii* compared to that of *C. rotang*. Depth of the soil occupied by the main roots of *C. thwaitesii* was much more than that of C. *rotang*. While the horizontal spread of the root system in *C. thwaitesii* was slightly more than that of *C. rotang*.

Number of lateral roots arising from the main roots in *C. rotang* was more than that of *C. thwaitesii*. Their length, thickness and the number of rootlets showed variation in the two species. All these were found to be more in *C. rotang* than in *C. thwaitesii*. Sub laterals were produced only in *C. rotang*.

After 24 months

C. rotang developed eight main roots. Average length of the main roots was 36.44 cm and thickness, 3.34 mm. The number of rootlets produced from the main roots were 276. Main roots with lesser than 14 cm length did not produce any rootlets. Soil depth occupied by the main roots on an average was 30.61 cm and the horizontal spread was 33 cm. Some of the main roots were seen to be disintegrated at this stage. More often, broken roots produced laterals from the broken region and some of these were found to reach the status of a main root. In certain cases, there was the presence of clustered laterals, of bristle nature reaching roughly 2-3 cm in length arising from the broken end of main roots.

Number of laterals arising from the main roots was on an average 58. They had a length of 8.27 cm and thickness of 0.78 mm and the number of rootlets from the laterals per plant was 776.

Number of sub laterals produced from the laterals were 14 per plant. The average length was 5.58 cm and thickness 0.54 mm, and the number of rootlets arising from the sub laterals was 131 per plant.

C. thwaitesii developed five main roots. Length of these main roots was 2.39 cm and thickness 1.70 mm and produced 136 rootlets on an average. Depth of the soil occupied by the roots from the surface was 20.92 cm. Horizontal spread of the entire root system was 12.5 cm. Some of the roots are showing disintegration at this stage. Main roots of less than 9.5 cm length did not produce laterals. Number of laterals produced on an average was 14. Their length was 6.29 cm and thickness 0.55 mm. Number of rootlets arising from the laterals per plant was 185. One of the lateral roots alone was found to produce sub laterals. 10 sub laterals were produced from this lateral root of 51 cm length. Number of sub laterals developed was 2. Length of the sub laterals was 4.25 cm and thickness 0.39 mm and produced 8 rootlets on an average.

Number of main roots, their length, thickness and number of rootlets arising from them were more in *C. rotang* when compared to *C. thwaitesii*. Soil depth occupied by the roots and horizontal spread of the root system were found to be more in *C. rotang*. Rate of disintegration was found to be more in *C. rotang*. Clustered laterals of bristle nature was seen in *C. rotang* alone. Number of laterals developing from the main roots was found to be more in *C. rotang*. Length and thickness of the laterals and the number of rootlets arising from them and the number of sub laterals produced from the laterals also were more in *C. rotang*. The length attained by the sub laterals, their thickness and the number of rootlets produced per plant were found to be more in *C. rotang*.

After 26 months

C. rotang developed nine main roots. Their length was 28.27 cm on an average, their thickness, 2.26 mm and the number of rootlets per plant was 206. Roots lesser than 3cm length did not produce rootlets at all. Depth of the soil occupied by the roots was 26.59 cm. Horizontal spread of the root system was 35.10 cm on an average. Laterals produced from the main roots per plant were 119 in number. Their length was 5.84 cm and thickness 0.62 mm. The number of rootlets present on the lateral roots were 1061 per plant. Number of sub laterals produced form the laterals per plant was 39. They had a length of 3.79 cm and thickness of 0.38 mm on an average and produced 257 rootlets from the sub laterals per plant (Fig. 12).

C. thwaitesii developed five main roots. Their length on an average was 21.39 cm and thickness was 1.70 mm. Number of rootlets produced per plant was 136. Roots lesser than 2 cm did not produce rootlets at all. Depth of the soil occupied by the roots was more or less 16.30 cm. Horizontal spread of the root system was 10.3 cm. Many of the main roots were found disintegrated at this stage. Laterals produced from the main roots on an average were 26. The length of the laterals was 7 cm and thickness 0.67 mm. Number of rootlets from the laterals were 346 per plant. Number of sub laterals produced from the laterals was 11. Their length was 5.53 cm and thickness 0.40 mm. Number of rootlets from sub laterals were 25 per plant (Fig. 13).

Number of main roots developed by *C. rotang* was more than that of *C. thwaitesii*. Length and thickness of the main roots was more in *C. rotang.* Number of rootlets in *C. rotang* was found to be more than that of *C. thwaitesii*. Maximum soil depth occupied by the roots was more in *C. rotang* than that of *C. thwaitesii*. However, horizontal spread of the root system was markedly more in C. *rotang* than that of *C. thwaitesii*. The number of laterals arising from the main roots was far more in C. *rotang* compared to *C. thwaitesii*. Length and thickness of these laterals were more in *C. thwaitesii* and the number of rootlets emerging from them were found to be more in *C. rotang* . The number of sub latterals developing from the laterals per plant was more in *C. rotang* than in *C. thwaitesii*. Length of the sub laterals was more in *C. thwaitesii*. Thickness of these sub laterals was more or less the same in both the species. Number of rootlets from the sub laterals was however found to be more in *Calamus rotang*.

After 28 months

C. rotang developed nine main roots. Length of the roots on an average was 36.18 cm and thickness 2.39 mm. Number of rootlets emerging from the main roots were 175. Main roots lesser than 10.5 cm did not produce any rootlets. Roots were showing disintegration at this stage also. Depth of the soil occupied by the roots was 32.56 cm.

The horizontal spread attained by the root system was 38.80 cm. Some of the rootlets were seen clustered at certain points on the main root. Number of the laterals arising from the main roots on an average was 98. Their length on an average was 5.66 cm and thickness 0.51 mm. Number of rootlets from the laterals per plant was 1083. At times, lateral roots were found to be arising from the main root in a clustered manner at a single point, sometimes, rootlets were also found to be emerging from the laterals at a single point. Number of sub laterals arising from the laterals was 67. Length of the sub laterals was 2.95 cm and thickness 0.27 mm. Number of rootlets were 360. Similar to that of rootlets, sub laterals also were found to be developing from the same point on the lateral root, thus giving a clustered appearance. At this stage of development, branches were seen to be developing from the sub laterals also. At times, these branches were also seen to be developing from the same point on the sub lateral.

C. thwaitesii developed nine main roots. Length of the roots on an average was 21.85 cm and thickness 2.02 mm. Number of rootlets emerging from the main roots were 158. Soil depth occupied by the roots was 4.91 cm. The horizontal spread of the root system on an average was 18.30 cm. Number of laterals developed were 36. Their average length was 6.14 cm and thickness, 0.58 mm. Number of rootlets on an average was 608. Many of the laterals were found disintegrated after a certain period of growth. Main roots having lesser than 9 cm length did not produce any laterals. The number of sub laterals developing from the laterals was 12. Length of these sub laterals on an average was 4.21 cm and thickness 0.50mm. Number of sub laterals per plant was 116 on an average.

The number of main roots developing from both the species was the same. Length of the main roots and the number of rootlets arising from them were more in *C. rotang* than in *C. thwaitesii*. However, the thickness of these roots was found to be slightly more in *C. thwaitesii* than that of *C. rotang*. Both, the soil depth occupied by the root system and the horizontal spread of the root system was found to be much more in *C. rotang* than that in *C. thwaitesii.* Clustering of rootlets on the main roots of *C. rotang* was a common feature which was not found in *C. thwaitesii.* Number of laterals arising from the main roots was found to be more in *C. rotang.* Length and thickness of these laterals developing from main roots was found to be slightly more in *C. thwaitesii.* However, the number of rootlets on laterals was found to be more in C. *rotang.* Disintegration rate of the laterals was found to be far more in *C. thwaitesii* at this stage. *C. rotang* showed the clustering of laterals (laterals developing in a clustered manner from a single point on the main root). Similarly clustered root lets developing from the laterals were also found in the same species. Number of sub laterals arising from the lateral roots were found to be more in *C. rotang.* Length, and thickness of the sub laterals and number of rootlets from the sub laterals were found to be more in *C. rotang.* Similar to that of laterals, sub laterals were also found to be clustering at times in *C. rotang.* Rootlets from the sub laterals also exhibited the same nature at times in this species. Branches were found to be developing from the sub laterals in *C. rotang* alone at this stage. The clustered appearance of branches developing from sub laterals was also seen at times, in *C. rotang.* No such clustering and development of branches from sub laterals were recorded in *C. thwaitesii.*

After 30 months

C. rotang developed 11 main roots. Length of the main roots on an average was 40.41 cm and thickness 2.65 mm and the number of rootlets were 273 per plant. Soil depth occupied by the root system was 33.37 cm and the horizontal spread attained by the root system was 25.40 cm. Main roots lesser than 9.5 cm length did not produce laterals. Several of the main roots were found to be undergoing disintegration. Number of laterals developing from the main roots on an average was 100. Length of the laterals were 6.89 cm and thickness 0.91mm. Number of rootlets developing from the laterals per plant was 940. Main roots with a length lesser than 9 cm never produced laterals. Mostly, laterals developed from roots with a length of 12cm or more. Almost all the laterals were producing root lets. The main roots were found to be showing signs of disintegration for a small length leaving the xylem intact, few cms lower down from the point of emergence. Number of sub laterals developing from the laterals on an average was 32. Length of these sub laterals were 4.68cm and thickness 0.85 mm and the number of rootlets from the sub laterals per plant was 282. Very rarely, branches were also seen to be developing from sub laterals. They ranged in number from one to three. Their length varied from 2 to 5 cm, thickness from 0.2 – 1 mm and the number of rootlets from four to 12.

C. thwaitesii developed 10 main roots. Their length on an average was 25.45 cm and thickness 2.39 mm. Number of rootlets were 163 per plant. Depth of soil occupied by the roots from the surface level was 24.12 cm on an average. Horizontal distance traversed by the root system was 17.20 cm. Main roots lesser than 10.5 cm length did not develop lateral roots at all. Number of laterals produced from the main roots were 43 on an average. Their length was 4.71 cm and thickness 0.68 mm. Number of rootlets from the laterals were 429. Most of the laterals produced rootlets. Very few lateral roots developed sub laterals. Number of sub laterals on an average was 5. Length of the sub laterals were 2.89 cm and thickness 0.50 mm. and the number of rootlets from the sub laterals were 25.

The number of roots developed by the plant, their length, thickness and the number of rootlets produced by them were found to be greater in *C. rotang* compared to that of *C. thwaitesii.* Both the soil depth occupied by the root system and the horizontal spread of the root system in *C. rotang* was found to be more than that of *C. thwaitesii.* The number of laterals produced, their length, thickness and number of rootlets produced from them were all greater in *C. rotang*. Signs of degeneration of main roots seen at certain positions in *C. rotang* was not commonly found in *C. thwaitesii*. Number of sub laterals, their length, thickness and number of rootlets produced from them were all more in *C. rotang* compared to *C. thwaitesii* . Branches arising from the sub laterals were not present in *C. thwaitesii* at this stage.

After 32 months

C. rotang developed 11 main roots. Length of the roots on an average was 31.78 cm and thickness 2.70mm. Number of rootlets from the main roots were 128. Soil depth occupied by the main roots was 27.65 cm. Maximum horizontal distance traversed by the root system was 35.60 cm. Main roots with 12 cm or more in length alone produced laterals. Number of laterals were 71 on an average with 7.01 cm length and 0.91 mm thickness. Number of rootlets arising from the laterals per plant was 698. Number of sub laterals arising form the laterals were 12. They had a length of 4.24 cm and thickness 0.73 mm. Number of rootlets from the sub laterals were 72.

C. thwaitesii developed 10 main roots. Their length on an average was 33.94 cm and thickness 2.39 mm. Number of rootlets was 216. Depth of soil occupied by the roots on an average was 28.21 cm. Maximum horizontal spread of the root system was 44.70 cm. Main roots having a length lesser than 13cm did not produce laterals. Number of laterals on an average was 80. They showed a length of 3.98 cm and thickness 0.52 mm. Number of rootlets from the laterals per plant was 763. Some of the laterals produced sub laterals. Number of sub laterals on an average was 15 with a length 3.22 cm and thickness 0.32 mm. The number of rootlets developed by the sub laterals on an average was 88.

The number of roots developed by the plant was slightly more in *C. rotang* while the length of the main roots were more in C. *thwaitesii.* Thickness was slightly more in *C. rotang*. However number of rootlets was found to be more in *C. thwaitesii*. The vertical depth and the horizontal spread of the root system also were slightly more in

C. thwaitesii compared to *C. rotang.* In both species, laterals were found to be developing from the main roots of more or less the same length. Number of laterals was more in *C. thwaitesii.* Length and thickness of the laterals arising from the main roots were more in *C. rotang*. However number of rootlets form the laterals per plant was more in *C. thwaitesii.* Number of sub laterals arising from the laterals was more in *C. thwaitesii.* Length and thickness of the sub laterals were more in *C. rotang.* However, number of rootlets developed by the sub laterals per plant was more in *C. thwaitesii.*

After 34 months

C. rotang developed 18 main roots. Length of the main roots on an average was 36.85 cm and thickness 3.00mm. Number of rootlets produced by the main roots per plant was 297. Generally, roots below 4 cm did not produce rootlets. Soil depth occupied by the root system was 30.97 cm. Horizontal spread attained by the root system was 57.80cm. One main root with 156 cm length was found to be entering into a cavity (void) and both the texture and shape of this root was found to be markedly different from the other roots. Main roots having less than 4 cm length were without any laterals. Number of laterals produced per plant was 164. Average length of the laterals was 6.06 cm and average thickness 0.82 mm. Number of rootlets developed from the laterals per plant was 1739. Laterals with a length of 2 cm or less in length never produced any rootlets. Laterals lesser than 1.5 cm did not produce any sub laterals. Number of sub laterals on an average was 57. Length of the sub laterals was 3.43 cm and thickness 0.43mm. Number of rootlets developed from sub laterals per plant was 410.

C. thwaitesii developed eight main roots. The roots had a length of 30.80 cm and thickness 2.50 mm. The roots were provided with 160 rootlets on an average. Depth of soil occupied by the roots from the surface was 28.41 cm on an average. Maximum horizontal distance traversed by the root system was 36.60 cm. Roots lesser than 7 cm length were devoid of rootlets. Main roots with length lesser than 10.5 cm. did not produce any laterals. Number of laterals developed from the main roots per plant was 34. Length of these laterals was 4.03 cm and thickness 0.67 mm. Number of rootlets from the laterals per plant was 287. Sub laterals were very few. Their number decreased to 2. Length of the sub laterals were 3.64 cm and thickness 0.37mm. The number of rootlets developed from these sub laterals were 8. No branches were seen to be arising from the sub laterals.

Main roots produced were more in *C. rotang*. Their length and also the number of rootlets developing from them were more in *C. rotang*. However, their thickness was found to be slightly more in *C. thwaitesii*. Soil depth occupied by the root system was found to be more in *C. rotang*. Horizontal spread of the root system was found to be remarkably more in *C. rotang*. Laterals were produced from main roots with more in length in *C. thwaitesii* than in *C. rotang*. Number of laterals developed from main roots was found to be much more in *C rotang* than in *C. thwaitesii*. Length and thickness of the laterals and also the number of rootlets developing from the laterals were found to be more in *C. rotang*. Number of sub laterals was far more in *C. rotang* when compared to *C. thwaitesii*. Even though the length and thickness of the sub laterals were more or less the same in both species, number of rootlets from these sub laterals was markedly more in *C. rotang*.

After 36 months

C. rotang at this stage developed 16 main roots. They had a length of 42.69 cm on an average and a thickness of 2.68mm. Number of rootlets developing from the main roots was 238. Roots greater than 7 cm length alone produced rootlets. Soil depth occupied by the main roots on an average was 37.81cm. Horizontal distance traversed by the root system was 65.82 cm. Main roots lesser than 7 cm length did not produce any laterals. Number of laterals arising from the main roots per plant on an average was 165. They had a length 4.98 cm and thickness of 0.81 mm. Number of rootlets produced by the laterals per plant on an average was 1324. Number of sub laterals produced from the laterals was 43. Length of the sub laterals were 3.57cm on an average and thickness, 0.52 mm. Number of rootlets arising from the sub laterals per plant was 242. Very rarely, branches were produced from the sub laterals. Number of branches arising from the sub laterals varied from 2-4. Their length ranged from 3-7 cm, thickness varied from 0.3 - 0.4 mm and number of rootlets varied in number from 2 - 8.

C. thwaitesii at this stage developed 19 main roots. Length of these roots on an average was 43.48 cm and thickness 3.45 mm. The main roots were seen to produce 254 rootlets per plant. Depth of soil occupied by the roots from the surface was 39.11 cm. Horizontal spread of the root system was 57.80 cm. Number of laterals arising from the main roots per plant was 134 on an average. Laterals were, however not produced from main roots having lesser than 3 cm. The laterals were having 4.85 cm length, and 0.83 mm thickness. Number of rootlets arising from these laterals per plant was 989. Sub laterals produced from the laterals were 14 on an average with 3.84 cm length, 0.49 mm thickness and 42 rootlets per plant. Branches of sub laterals varied in their number from 1-5. Their length varied from 1.2 – 2.8 cm thickness and varied from 0.2-1.5 mm. Number of rootlets developing from laterals varied in their number from 2-26.

C. thwaitesii produced more number of main roots than *C. rotang*. Length of the main roots, thickness of the main roots and the number of rootlets were more in *C. thwaitesii* when compared with *C. rotang*. Soil depth occupied by the roots in both the species were more or less the same. Horizontal distance traversed by the root system was markedly more in *C. rotang* when compared to *C. thwaitesii* . Number of laterals arising from the main roots were more in *C. rotang*. Length and thickness of the laterals were almost the same in both species. Number of rootlets developing from the laterals and number of sub laterals produced from the laterals were more in *C. rotang* than in *C. thwaitesii*. Length of these sub laterals was more in *C. thwaitesii* while their thickness was more in

C. rotang. The number of rootlets arising from them was markedly more in *C. rotang* than in *C. thwaitesii* . Branches arising from the sub laterals were more or less the same in both the species. Their length, thickness as well as the number of rootlets were more in *C. thwaitesii*.

After 38 months

C. rotang developed 25 main roots. Lengths of these main roots were 38.70 cm on an average, thickness of the roots were 2.88mm. Number of rootlets arising form the main roots were 290 on an average. Soil depth occupied by the roots from the surface was 29.03 cm. Maximum horizontal distance traversed by the root system was 91.80 cm. Laterals were produced by almost all the main roots. Number of laterals were 155. Length of the laterals were 6.24 cm and thickness 1.04 mm. Number of rootlets arising from the laterals per plant on an average was 1095. Sub laterals were found to arise from many of the laterals. Number of sub laterals on an average was 43. Length of these sub laterals were 4.39 cm, thickness 0.74 mm and the number of rootlets arising form these sub laterals per plant was 242. Branches arising from the sub laterals were rare. Only one branch was seen to be arising from a sub lateral. The branch emerging from the sub lateral was of 3 cm length, 1 mm thickness and provided with 8 rootlets (Fig. 14).

C. thwaitesii. The plant developed 28 main roots. Length of the roots on an average was 45.74 cm, thickness was 3.68 mm and the number of rootlets on an average was 287. Soil depth occupied by the root system was 38.15 cm . Horizontal distance traversed by the root system was 61.60 cm. Number of laterals developing from the main roots per plant on an average was 201. Lengths of these laterals were 5.02 cm, thickness 0.81 mm and number of rootlets 1865. Numbers of sub laterals emerging from the laterals were 35. Length of these sub laterals were 4.06 cm, thickness 0.52 mm and number of rootlets were 207 (Fig. 15).

Fig. 12 *C. rotang* (26 months)

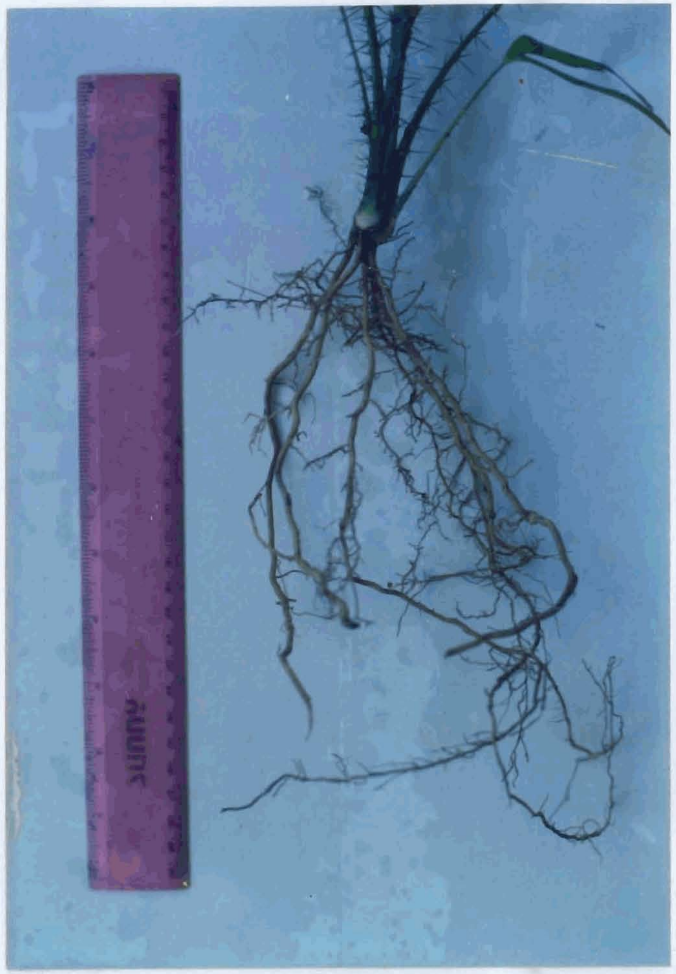


Fig. 13 *C. thwaitesii* (26 months)

Root system of *Calamus* at different stages of growth

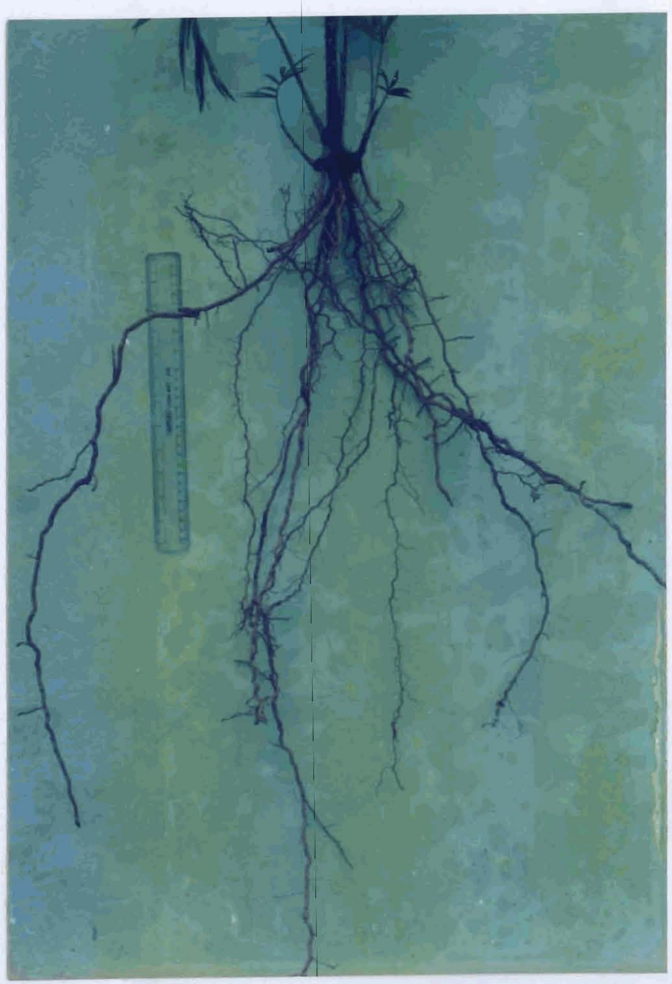


Fig. 14 *C. rotang* (38 months)

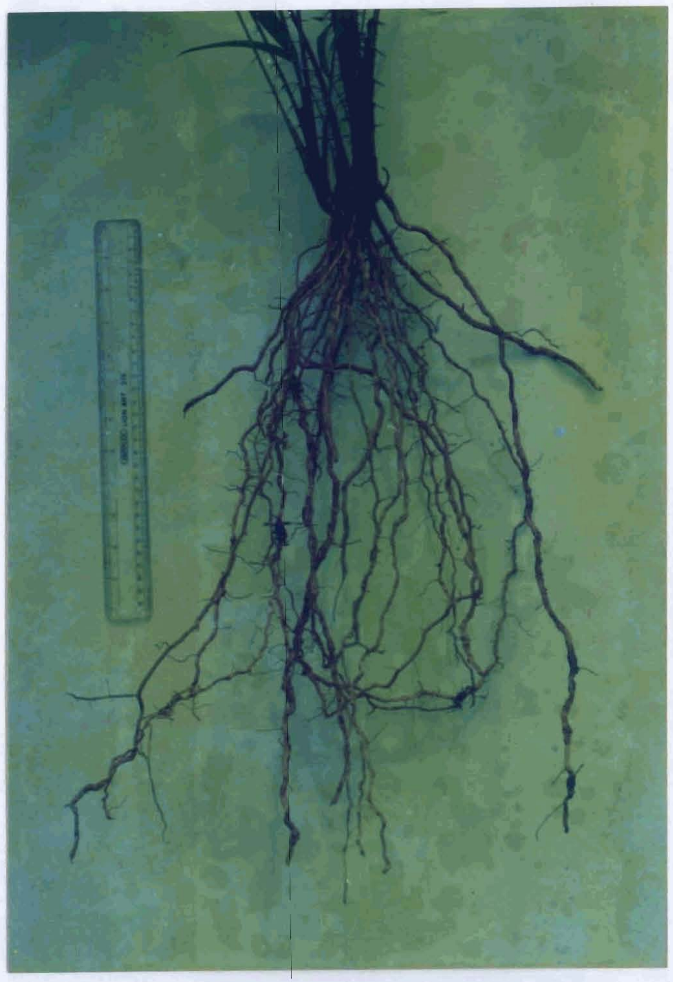


Fig. 15 *C. thwaitesii*(38 months)

Root system of *Calamus* at different stages of growth

C. thwaitesii produced more number of main roots ,possessing more length as well as thickness while the number of rootlets were found to be more or less the same in both species. Vertical depth of the soil occupied by the root system was more in *C. thwaitesii*. However, the horizontal spread of the root system was remarkably more (more than twice) in *C. rotang* when compared to *C. thwaitesii* . Number of laterals developing in *C. thwaitesii* was more than that in *C. rotang*. Length and thickness of these laterals in *C. rotang* were more than that of *C. thwaitesii*. However, number of rootlets produced from the laterals in C. *thwaitesii* was more than that of *C. rotang*. Number of sub laterals emerging from the laterals, their length, thickness and number of rootlets arising from them were all slightly more in *C. rotang* compared to *C. thwaitesii*. Branches from sub laterals were not present in *C. thwaitesii*. There was only one branch from the sub lateral in *C. rotang*. The branch was of 3 cm length, 1 mm thickness and provided with 8 rootlets.

4.2 Rhizome development

Rhizome development started in the two species along with the development of multiple stems. Vegetative buds in the axils of seedling leaves developed into suckers. These suckers developed repeated growth characteristics of parent stem (Fig. 15a. and Fig. 15b).

C. rotang and *C. thwaitesii* differed in the time of elongation of the primary stem. While primary shoot elongated before the production of suckers in *C. rotang*, 3-4 suckers were produced before the primary shoot elongation in *C. thwaitesii*.

Fig. 15a Sucker formation in *C. rotang*

Fig. 15b Sucker formation in *C. thwaitesii*

4.3 Root growth in relation to soil properties

Root length, total root weight, fine root weight, and rooting density at different radial distances from the plant (0, 10 & 30 cm) were recorded at different soil depths (0-15, 15-30, 30-45 and 45-60 cm). Data obtained from the root fragments present in the collected soil core samples has been tabulated in the chapter on results.

Physical and chemical properties

Physical and chemical properties of the soil have been analysed by taking the core samples at different soil depths and radial distances. The analytical methods were adopted as described under the chapter on 'materials and methods' and the data recorded were given under chapter 'results'

Chapter 5.

RESULTS

5. RESULTS

Results are arranged in the following three sections.

1. Root morphology and growth pattern
2. Rhizome development
3. Root growth in relation to soil properties

5.1 ROOT MORPHOLOGY AND GROWTH PATTERN

From the observations taken a comparative study between the species was made for the following factors

5.1.1 Origin of root system
5.1.2 Development of secondary and lateral roots
5.1.3 Number of roots
5.1.4 Length and diameter of roots
5.1.5 Rate of growth with respect to length and diameter
5.1.6 Spatial orientation
5.1.7 Soil volume exploited
5.1.8 Effective soil volume
5.1.9 Rooting density
5.1.10 Root intensity
5.1.11 Root surface area
5.1.12 Soil binding capacity
5.1.13 Shoot-root relationship.

5.1.1 Origin of root system

The mode of seed germination and the nature of origin of roots in *C. rotang* and *C. thwaitesii* were similar. The germination of seeds was of adjacent ligular type, which is the general type reported in palms (Tomlinson, 1961). The primary root stopped its growth 4 to 5 months after germination.

5.1.2. Development of secondary and lateral roots

By the time the primary root system became non functional, secondary roots (adventitious roots) emerged from the lower end of the axis which had already elongated obconically. The first secondary root emerging was found very close to the base of the primary root. This secondary root elongated producing several laterals simultaneously. A large number of root lets was produced on these laterals. About 4-5 months after germination, the primary root gradually became non functional. At this stage, a seedling had 2-5 main roots producing laterals which in turn produced sublaterals. When any of the main roots were broken or damaged, secondary laterals were produced immediately behind the injury. Whenever the root tip was destroyed, it was usually replaced by one or more branch roots, which grew out immediately behind this dead end.

As the plants grew, there was an increase in the number of secondary roots, their length as well as diameter. The laterals were produced from the 1st year onwards while the sublaterals from the 2nd year onwards.

Root growth of the two species *viz. C. rotang* and *C. thwaitesii* were compared separately for each period (2 months interval) with respect to each of the growth parameters such as number of roots, their length, diameter, and spatial orientation.

5.1.3 Number of roots

Seedlings of the two species developed 1 or 2 main roots in the initial stages. At the end of 14 months, both *C. rotang* and *C. thwaitesii* produced 5-8 main roots. At the end of 26 months, plants of *C. rotang* had 14-27 main roots while plants of *C. thwaitesii* had only 8-10 main roots. At the end of 38 months, both the species had almost the same number of main roots.

Laterals were produced from 6th month onwards in *C. rotang* and from 8th month onwards in *C. thwaitesii*. While sublaterals developed from 10th month onwards in *C. rotang*, they were formed from 18th month onwards in *C. thwaitesii*.

The number of main roots and their laterals increased with age in both the species. Analysis of variance on data with respect to the number of roots showed that there was no significant difference between the species during 14th month and also during 38th month, where as the two species differed significantly with regard to the number of main roots, laterals and sublaterals during 26th month. It indicated that the two species differed significantly in the number of roots formed in the second year. These, when subjected to analysis of variance revealed significant differences between the two species with regard to both the number of main roots as well as laterals and sublaterals only at 26th month (Table 1).

Table 1. Comparison of mean number of roots

Period (months)	Main roots			Laterals			Sublaterals		
	Cr	Ct	R	Cr	Ct	R	Cr	Ct	R
2	2	1	*ns*	--	--	--	--	--	--
14	5	5	*ns*	9	7	*ns*	--	--	--
26	15	8	*s*	119	26	*s*	39	11	*s*
38	25	28	*ns*	155	201	*ns*	43	35	*ns*

n = 5 replicates

Cr – *C. rotang*, Ct – *C. thwaitesii*, R – Result, *s* – significant, *ns* – Non significant

5.1.4 Length and diameter of roots

A comparison of mean values of root length between the species at different periods showed that during the early stages, the length attained by the main roots of both the species was almost similar. Laterals and sublaterals also exhibited the same trend up to 26 months. Analysis of variance on data with respect to the length of the root showed that there was significant difference in the length of the laterals between the two species at the end of 38th month. No significant difference was obtained between the two species with respect to the length of main roots and sublaterals during the period of study (Table 2).

Table 2. Comparison of mean length (cm)

Period (months)	Main roots			Laterals			Sublaterals		
	Cr	Ct	R	Cr	Ct	R	Cr	Ct	R
2	10.68	14.39	*ns*	--	--	--	--	--	--
14	13.39	16.40	*ns*	5.56	4.76	*ns*	--	--	--
26	28.27	19.94	*ns*	5.84	7.00	*ns*	3.79	5.53	*ns*
38	38.70	45.74	*ns*	6.24	5.02	*s*	4.39	4.06	*ns*

n = 5 replicates

Cr – *C. rotang*, Ct – *C. thwaitesii* R – Result, *s* – Significant, *ns* – Non significant

Comparison between the two species with respect to rate of total root length showed that during the second year of growth there was marked increase in *C. rotang* when compared to *C. thwaitesii*. On the contrary during the 3rd year, a marked increase was noted in *C. thwaitesii* when compared to *C. rotang.* (Fig. 16)

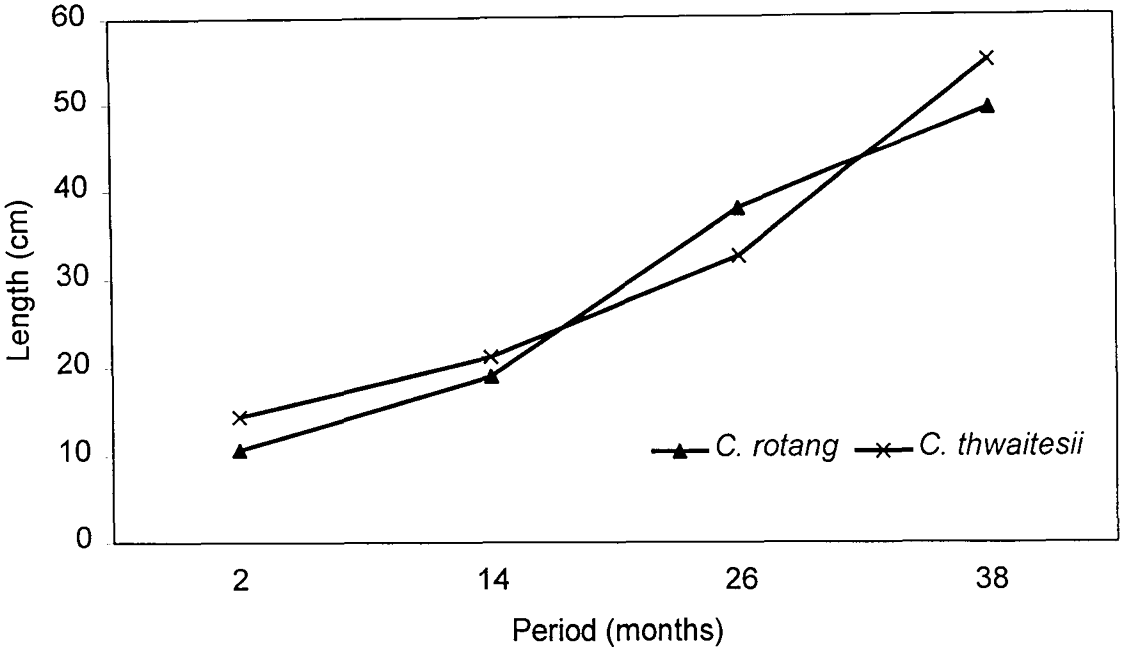


Fig. 16. Comparison of total root length

The regression equation for root length was fitted separately for *C. rotang* and *C. thwaitesii* (Table 4). Regression equation fitted for root length of *C. rotang* showed that 68% of the variation in the root length could be explained by age of the plant. Similarly in the case of *C. thwaitesii*, 42% of the variation in root length could be explained by the age of the plant.

Diameter of roots also increased gradually with age. Analysis of variance on data with respect to the diameter of roots showed significant difference between the two species with respect to the main roots at the end of 14th month. However, the two species did not differ significantly at the end of 26th month. At the end of 38th month significant difference was noted between the two species with respect to the diameter of laterals (Table 3.).

Table 3. Comparison of mean diameter (mm)

Period (months)	Main roots			Laterals			Sublaterals		
	Cr	Ct	R	Cr	Ct	R	Cr	Ct	R
2	0.88	1.18	*ns*	--	--	--	--	--	--
14	1.28	1.64	*s*	0.25	1.19	*ns*	--	--	--
26	2.26	2.75	*ns*	0.62	0.67	*ns*	0.38	0.40	*ns*
38	2.88	3.68	*ns*	1.04	0.81	*s*	0.74	0.52	*ns*

n = 5 replicates

Cr – *C. rotang*, Ct – *C. thwaitesii*, R – Result, *s* – Significant, *ns* – Non significant

Comparison between the two species with regard to the rate of the total root diameter revealed that the rate of total root diameter in *C. thwaitesii* was more than that in *C. rotang* during the entire period of study (Fig. 17)

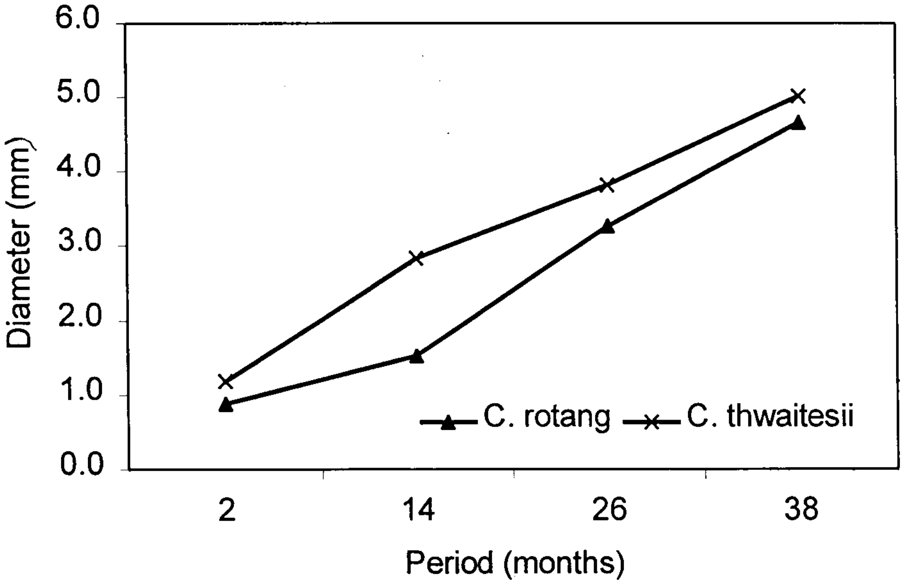


Fig. 17. Comparison of total root diameter

The regression equation for root diameter was fitted separately for *C. rotang* and *C. thwaitesii* (Table 4)

In *C. rotang,* regression equation fitted for root diameter showed that 78 % of the variation in root diameter could be explained by age of the plant. Similarly in the case of regression equation for *C. thwaitesii*, 57 % of the variation in root diameter could be explained by age of the plant (Table 4)

Table 4. Models fitted for different characteristics using regression

Species	Character (Y)	Model	Adj. R^2
C. rotang	Root length	Y = 1.6491 + 0.0649 X (0.1172) (0.0046)	0.6836
C. thwaitesii	Root length	Y = 2.2175 + 0.0396 X (0.1159) (0.0047)	0.4214
C. rotang	Root diameter	ln (Y) = 1.5921 + 0.0537 X (0.0769) (0.0030)	0.7754
C. thwaitesii	Root diameter	ln (Y) = 1.3514 + 0.0337 X (0.0736) (0.0030)	0.5687

Figures in parenthesis indicate standard error of the coefficients

X = months

5.1.5 Rate of growth with respect to length and diameter

Rate of growth per root with respect to length of the main roots, lateral roots and sub laterals was calculated separately for each year in the two species of *Calamus*. A comparison was made between the two species with respect to rate of elongation (Table 5).

Main roots in *C. rotang* attained a higher rate of elongation in the 1st year (25%) and 2nd year (111%) compared to that of *C. thwaitesii* having 14% and 30% elongation of main roots in the 1st and 2nd year respectively. However, in both the species, the elongation rate of main roots in 2nd year, was found to be more than that of 1st year. Root of *C. thwaitesii* elongated more compared to *C. rotang*. Unlike in the 2nd year, in the 3rd year a drastic decline in the elongation rate to 37 % was obtained for the main root in *C. rotang* while an increase from 30 % to 115 % occurred in the case of *C. thwaitesii.*

Lateral root of *C. rotang* achieved 5 % elongation in the 2nd year and 7 % elongation in the 3rd year. Lateral root of *C. thwaitesii* possessed an increased rate of elongation (ie) 51 % in 2nd year. But in the 3rd year, when the elongation rate of lateral root showed an increase from 5 % to 7% in *C. rotang*, *C. thwaitesii* showed a negative rate of elongation (30 %) which means that the lateral of *C. thwaitesii* showed signs of degeneration during the 3rd year.

Table 5. Rate of elongation

Period (year)	Main root		Laterals		Sublaterals	
	Cr	Ct	Cr	Ct	Cr	Ct
Firat	0.25	0.14				
Second	1.11	0.30	0.05	0.51		
Third	0.37	1.15	0.07	-0.3	0.16	-0.27

Cr – *C. rotang*, Ct – *C. thwaitesii*

In the 3rd year, sublaterals showed an elongation of 16% per root in *C. rotang*, while in *C. thwaitesii* there was a decrease in the length of sublaterals at the rate of 27% per root (Table 5).

It could be inferred from the data that in both the species when there was an increased elongation rate in main roots, there was a decrease in the growth of laterals and *vice-versa*. This was specifically seen in *C. thwaitesii* with respect to its laterals and sublaterals which showed signs of degeneration during the 3rd year.

Rate of increase in thickness of the main roots, laterals and sublaterals in each is shown in table 6.

At the end of 1st year, when the rate of increase in thickness with respect to the main roots was 45% per root in *C. rotang*, it was 39% per root in *C. thwaitesii*. At the end of 2nd year this was increased to 77% per root in *C. rotang* and 81% per root in *C. thwaitesii*. At the end 3rd year, main roots of *C. rotang* showed an increase of 27% per root in their thickness while that of *C. thwaitesii* showed an increase of 24% per root.

Table 6. Rate of increase in thickness

Period (year)	Main root		Laterals		Sub laterals	
	Cr	Ct	Cr	Ct	Cr	Ct
First	0.45	0.39				
Second	0.77	0.81	1.48	-0.43		
Third	0.27	0.24	0.68	0.2	0.95	0.28

Cr – *C. rotang*, Ct – *C. thwaitesii*

With respect to the laterals, rate of increase in thickness of a root at the end of 2nd year was 148% per root in *C. rotang*, while that of *C. thwaitesii* showed a decline of 43% in the thickness of a root. At the end of 3rd year, while each lateral root of *C. rotang* showed an increase of 68% in its thickness, that of *C. thwaitesii* showed only 20% increase.

Rate of increase in thickness of each sub lateral in the 3rd year was 95% in *C. rotang*, while it was only 28% in *C. thwaitesii* (Table 6.).

5.1.6 Spatial orientation

Vertical growth was seen to be prominent in rattan root systems at its early stages. The primary root grew up to about 11.45 cm in *C. rotang* and 14.13 cm in *C. thwaitesii* within a period of 2 months. At the end of 1st year, vertical growth of the roots attained a length of 13.33 cm and 15.34 cm in *C. rotang* and *C. thwaitesii* respectively. The horizontal spread of the root system at this stage was 9.26 cm in *C. rotang* and 12.30 in *C. thwaitesii.* At the end of 26 months, root system of *C. rotang* showed a vertical growth of 26.35 cm while that of *C. thwaitesii* showed 16.51 cm. Horizontal spread of the root system at this stage was 48.70 cm in *C. rotang* and 10.30 cm in *C. thwaitesii.* A reverse trend in root growth was seen during the 2nd year, the species *C. rotang* exhibiting an increased vertical growth and horizontal growth. At the end of 38 months, this trend was again reversed with respect to the vertical spread of the root system, *C. rotang* was having 29.84 cm and *C. thwaitesii* 39.05 cm. However horizontal spread of the root system was more in *C. rotang* (91.80 cm) compared to that of *C. thwaitesii* (61.60 cm) (Table 7.).

Analysis of variance on data pertaining to horizontal growth of roots showed that there was no significant difference between the species during 14th month and also during 38th month, where as the two species differed significantly during 26th month. The same trend was observed in the case of vertical growth of roots also. It indicates that the two species differed significantly in the horizontal as well as vertical growth of roots during the 2nd year.

Table 7. Comparison of horizontal and vertical spread (cm)

Period (months)	Horizontal spread			Vertical spread		
	Cr	Ct	R	Cr	Ct	R
2	--	--	--	11.45	14.13	*ns*
14	9.26	12.30	*ns*	13.33	15.34	*ns*
26	48.70	10.30	*s*	26.35	16.51	*s*
38	91.80	61.60	*ns*	29.84	39.05	*ns*

n = 5 replicates

Cr – *C. rotang*, Ct – *C. thwaitesii*, R – Result, *s* – significant, *ns* – Non significant

5.1.7 Soil volume exploited

In general, soil volume exploited by the root system of rattans showed a tremendous increase with age of the plant. In the nursery the plant seldom has enough soil at its disposal to allow optimal development of its root system. The information on exploited soil volume in the two species of *Calamus* for each year can be made use of in overcoming this drawback. Moreover effective soil volume can be calculated on knowing the volume of soil exploited.

It was seen that the soil volume exploited by the root system of *C. rotang* in the 1st year (876.52 cm^3) was much lesser than that of *C. thwaitesii* 1842.75 (cm^3). While soil volume exploited by the roots of *C. rotang* showed a drastic increase (25769.33 cm^3) in the 2nd year, there was not much difference in the exploited soil volume in *C. thwaitesii* (1820.99 cm^3). However soil volume exploited in the 3rd year by the root system of *C. rotang* and *C.*

thwaitesii was fairly large. While it reached to 192219.32 cm^3 in *C. rotang* it was 113741.94 cm^3 in *C. thwaitesii*. Thus soil volume exploited by the root system of *C. rotang* in a 3year old plant was much more compared to that of *C. thwaitesii* of same age (Table 8.).

Table 8. Comparison of soil volume exploited

Period	Soil exploited (cm^3)	
(year)	Cr	Ct
First	876.524	1842.75
Second	25769.33	1820.99
Third	192219.3	113741.94

n=5 replicates

Cr – *C. rotang*, Ct – *C. thwaitesii*

5.1.8 Effective soil volume

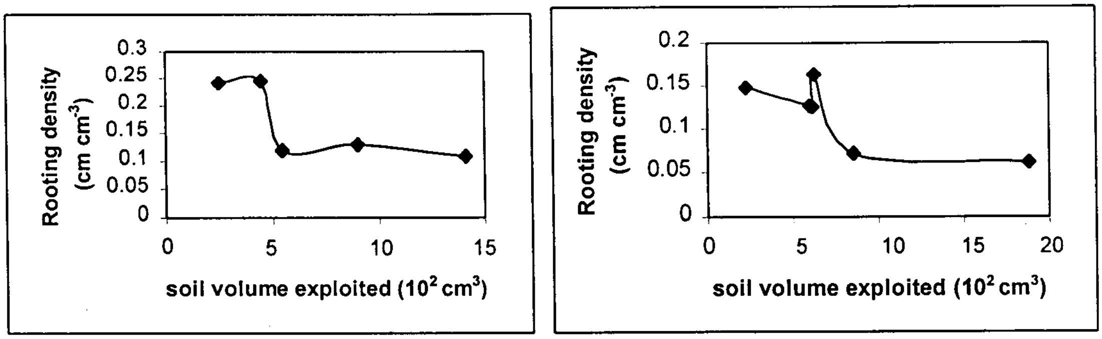
An idea regarding the effective soil volume for the two species of *Calamus* in each year will help in nursery practices such as deciding the size of polybags, volume of soil to be filled in the bags etc.

In the 1st year effective soil volume in *C. rotang* was 446.78 cm^3 while in *C. thwaitesii* it was 631.59 cm^3 (Fig. 18.). In the 2nd year, effective soil volume was more than that in 1st year. While *C. rotang* had an effective soil volume of 3812.6 cm^3, it was only 1376.21 cm^3 in *C. thwaitesii* (Fig. 19.).. *C. rotang* had a drastic increase in the effective soil volume, in the 3rd year reaching upto 17767.25 cm^3, while *C. thwaitesii* was with only 1376.21 cm^3 of soil (Fig. 20.), (Table 9.).

Table 9. Comparison of effective soil volume

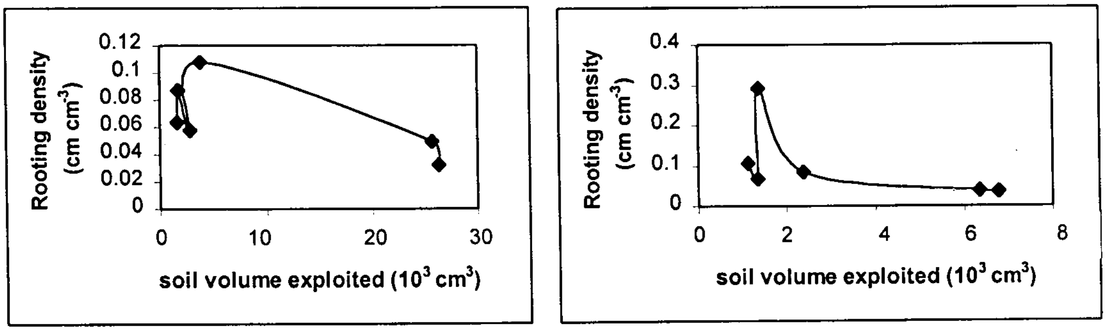
Period (year)	Effective soil volume (cm^3)	
	C. rotang	*C. thwaitesii*
Firast	446.78	631.59
Second	3812.60	1376.21
Third	17767.25	1376.21

n=5 Replicates



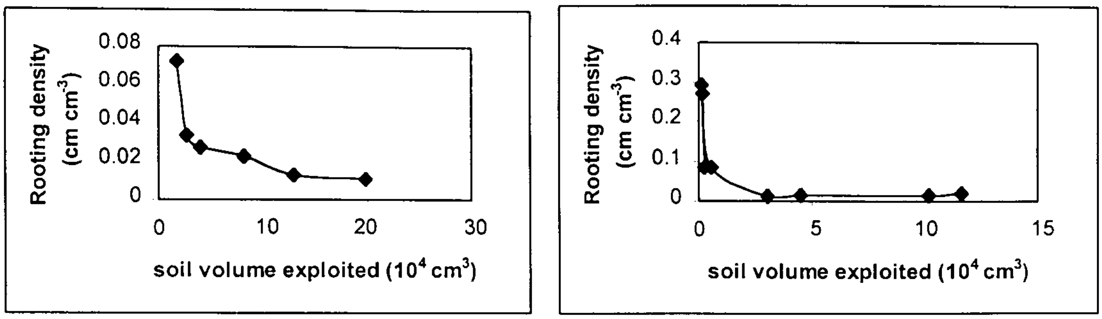
C. rotang *C. thwaitesii*

Fig.18. Comparison of effective soil volume at the end of 1st year .



C. rotang *C. thwaitesii*

Fig. 19. Comparison of effective soil volume at the end of 2nd year



C. rotang *C. thwaitesii*

Fig. 20. Comparison of effective soil volume at the end of 3rd year

5.1.9 Rooting density

Rooting density is often found to affect the balance of nutrient uptake from different parts of the soil profile which in turn may influence the growth of the seedling. In this study, rooting density was calculated for the main roots, laterals and sublaterals separately for each year. In both the species, rooting density was found to decrease with increase in the soil volume exploited.

Rooting density with respect to the main roots at the end of the 1st year in *C. rotang* was 0.0765 cm cm^{-3} while that of *C. thwaitesii* was only 0.0445 cm cm^{-3}. When the rooting density with respect to main roots of *C. rotang* decreased to 0.0165 cm cm^{-3} at the end of 2nd year, it increased to 0.0935 cm cm^{-3} in *C. thwaitesii* and the decrease in the exploited soil volume in *C. thwaitesii* during this period accounts for this. Rooting density at the end of 3rd year declined to 0.005 cm cm^{-3} in *C. rotang* with respect to its main roots while that of *C. thwaitesii* declined to 0.0112 cm cm^{-3} during this period.

Rooting density with respect to the laterals of the two species was also calculated. Rooting density of *C. rotang* at the end of 1st year was 0.05716 cm cm^{-3} while that in *C. thwaitesii* was 0.01816 cm cm^{-3}. A two year old plant of *C. rotang* had 0.0274 cm cm^{-3} rooting density while *C. thwaitesii* of same age had a higher rooting density of 0.1027 cm cm^{-3}. *C. rotang*, at the end of 3rd year, had a rooting density of 0.00475 cm cm^{-3} while *C. thwaitesii* had 0.0080cm cm^{-3}.

Rooting density with respect to sublaterals of *C. rotang* during the 2nd year was 0. 0585 cm cm^{-3} while that of *C. thwaitesii* was 0.0338 cm cm^{-3}. 3 year old *C. rotang* had a rooting density of 0.0009 cm cm^{-3} with respect to its sub laterals while *C. thwaitesii* had a rooting density of 0.0014 cm cm^{-3} (Fig. 21).

Total rooting density of the plants was found to be generally decreasing with age. Total rooting density of a 3 year old *C. rotang* was 0.0106 cm cm^{-3} while that of *C. thwaitesii* of same age had a higher rooting density of 0.0206 cm cm$^{-3.}$ (calculated from Table 10).

Table 10.Comparison of Rooting density

Period (year)	*C. rotang*				*C. thwaitesii*			
	Soil Volume (cm^3)	Rooting density (cm per cm3)			Soil Volume (cm^3)	Rooting density (cm cm^{-3})		
		Main	Lateral	Sub lateral		Main	Lateral	Sub lateral
First	876.52	0.0765	0.0571	0.0000	1842.75	0.0445	0.0181	0.0000
Second	25739.33	0.0165	0.0274	0.0585	1820.99	0.0935	0.1027	0.0338
Third	192219.32	0.0050	0.0047	0.0009	113741.94	0.0112	0.0080	0.0014

n= 5 replicates

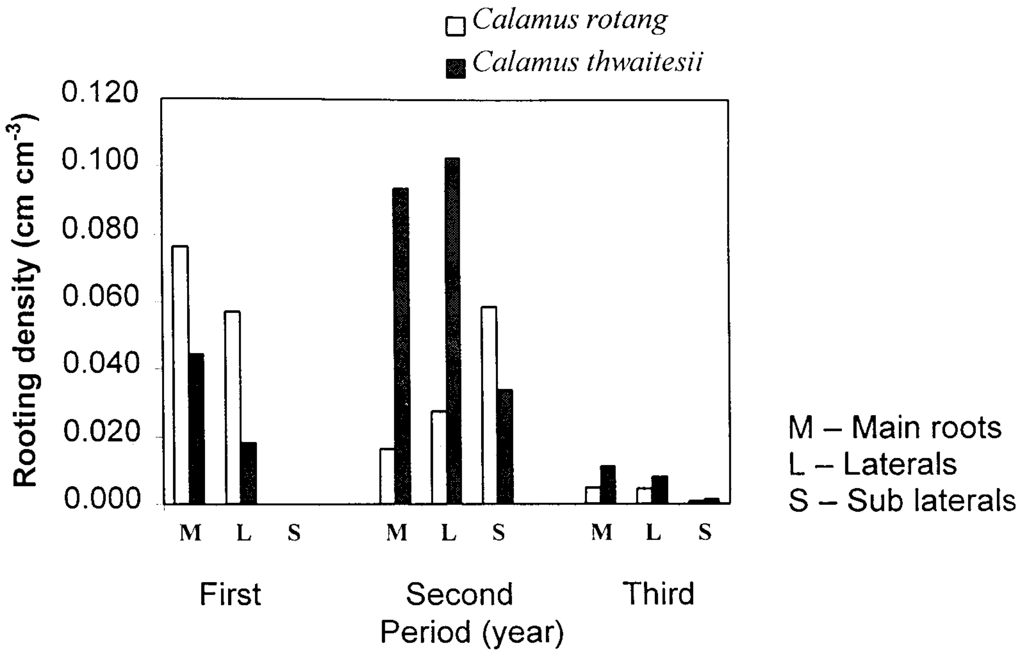


Fig. 21. Comparison of rooting density

5.1.10 Root intensity

Total root intensity and the absorbing root intensity contributed by the fine roots at different depths and different radial distances in *C. rotang* and *C. thwaitesii* were calculated and compared (Table 11).

Percentage of total roots was more at the surface layer (0 – 15) cm in both the species (57 % in *C. rotang* and 68 % in *C. thwaitesii*). Percentage contribution of absorbing roots in the total root intensity of the two species was also maximum at the surface layer (46 % in *C. rotang* and 57 % in *C. thwaitesii*).

Table 11. Depth wise distribution of total roots and contribution of fine roots

Depth (cm)	Total roots (%)		Fine roots (%)	
	C. rotang	*C. thwaitesii*	*C. rotang*	*C. thwaitesii*
0-15	57 %	68 %	46 %	57 %
15 - 30	20 %	18 %	17 %	16 %
30 – 45	15 %	8 %	13 %	8 %
45 – 60	8 %	6 %	7 %	6 %

Cr – *C. rotang*, Ct – *C. thwaitesii*

With respect to radial distance, percentage of total roots was maximum at 10 cm away from the centre of the rooting zone in *C. rotang* (37 %) while a maximum number of roots were seen very closer to the rooting zone in *C. thwaitesii* (46 %). Percentage contribution of absorbing roots in the total root intensity of *C. rotang* reached a maximum of 33 % at 10 cm away form the center of the rooting zone and that of *C. thwaitesii* reached maximum of 36 % closer to the rooting zone (Table 12).

Thus in *C. rotang* 83 % of the total root intensity was the contribution of fine roots while in *C. thwaitesii*, it went upto 87 %. From the above results, it could be inferred that the absorbing zone was at 0 – 30 cm depth and at 10 cm away from the rooting zone in *C. rotang* and at 0 – 30 cm depth close to the rooting zone in *C. thwaitesii.*

Table 12. Lateral distribution of total roots and contribution of fine roots

Radial distances (cm)	Total roots (%)		Fine roots (%)	
	Cr	Ct	Cr	Ct
0	33 %	46 %	24 %	36 %
10	37 %	29 %	33 %	27 %
30	30 %	25 %	26 %	24 %
Total	100 %	100 %	83 %	87 %

Cr – *C. rotang*, Ct – *C. thwaitesii*

5.1.11 Root surface area

Root surface area is considered as the criteria for its absorptive power. The root surface area of the two species was calculated separately for 4 periods. Surface area contributed by the fine roots was also calculated separately (Table 13.).

Table 13. Comparison of root surface area per plant

Period (months)	Root surface area (cm^2)					
	C. rotang			*C. thwaitesii*		
	<2 mm	>=2m	Total	<2 mm	>=2m	Total
2	6.01	0	6.01	8.59	0	8.59
14	28.67	4.19	32.86	20.61	22.47	43.08
26	178.13	338.32	516.45	74.81	162.04	236.85
38	365.81	997.28	1363.09	284.36	1643.60	1928.02

Root surface area per plant (RSA of fine roots < 2 mm and >= 2 mm diameter are given separately)

It was found that at 2 months, root surface area of *C. rotang* was 6.01 cm^2 per plant. While that of *C. thwaitesii* was 8.59 cm^2 per plant. While *C. rotang* was having a root surface area of 32.86 cm^2 in the 14th month, *C. thwaitesii* was having 43.08 cm^2. However in the 26th month, *C. rotang* had greater root surface area per plant (516.45 cm^2) compared to that of *C. thwaitesii* (236.85 cm^2). This trend was getting reversed at the end of 3rd year. That is, at 38th month, *C. rotang* had lesser surface area (1363.09 cm^2) than that of *C. thwaitesii* (1928.02 cm^2). Contribution of fine roots in the total surface area at this stage was found to be indeed more in *C. rotang* (365.81 cm^2) when compared to *C. thwaitesii* (284.36 cm^2) (Table 13.).

5.1.12 Soil binding capacity

Binding capacity of a plant determines whether it could be made use of in soil conservation. In this study, soil binding capacity of the two species of *Calamus* considering laterals and sublaterals of the root system was calculated for each year separately. In the first year, when *C. rotang* had binding capacity of 174.7, *C. thwaitesii* had 149.6 as binding factor. At the end of 2nd year when the binding factor increased to 302.7 in *C. rotang*, a marked increase was found in *C. thwaitesii* from 149.6 to 401.4. By the end of 3rd year, *C. rotang* was with a binding factor of 334 and *C. thwaitesii* with a binding factor of 285.4. It was seen that maximum soil binding capacity during the study period was shown by a 3 year old *C. rotang* (Table 14). The binding factor determined in the two species of *Calamus* showed that they could be good soil binders.

Table 14. Comparison of soil binding factor

Period (year)	*C. rotang*	*C. thwaitesii*
First	174.7	149.6
Second	302.7	401.4
Third	334	285.4

5.1.13 Shoot-root relationship

In rattan, even though the root system shows an increase in both vertical and horizontal spread, their shoot system remains in the rosette stage for the first 3-4 years of seedling growth. Hence in order to see whether the shoot develops along with the root during this stage, a comparative study of the dry weight of shoot and root was conducted.

Table 15. Correlation coefficient between dry weights of shoot and root for four periods

	DS_1	DS_2	DS_3	DS_4
DR_1	0.72^{**}			
DR_2		0.82^{**}		
DR_3			0.89^{**}	
DR_4				0.94^{**}

DS - Dry weight of shoot

DR - Dry weight of root

On computing the correlation coefficients between the shoot weight and root weight period wise, a highly significant positive correlation was obtained (Table 15). This shows that there was a simultaneous increase of biomass of shoot and root (Fig. 22.) and even though the shoot remained in the rosette stage, its biomass increased.

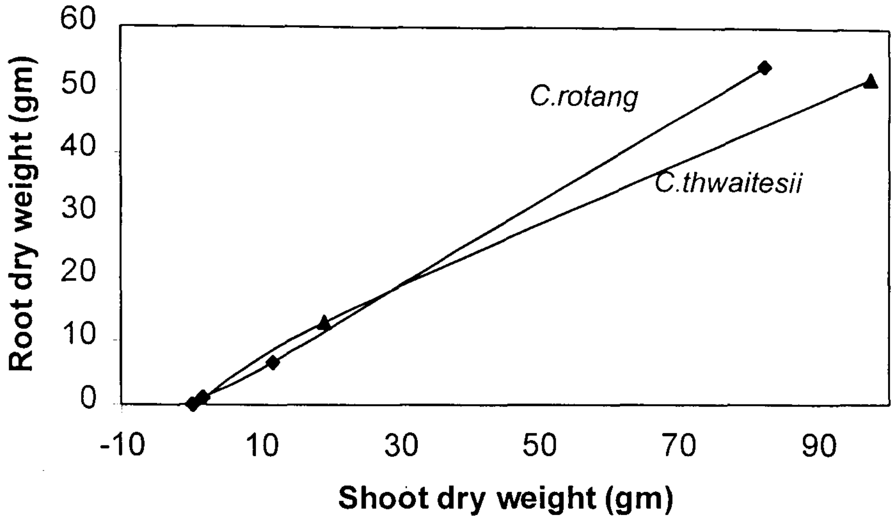


Fig. 22. Shoot - Root relationship

Mean values of the shoot-root ratio of dry weight and fresh weight of both species for the four periods are shown in the Table 16. It was revealed that there was no significant difference between the two species with respect to shoot - root ratio of dry weight for the entire period. But in the case of shoot-root ratio of fresh weight, a significant difference between species was observed in the 3rd and 4th period. Shoot-root ratio of fresh weight was higher in *C. rotang* than in *C. thwaitesii* (Table 16.).

Table 16. Shoot - root ratio

Period (months)	Dry weight			Fresh weight		
	C. rotang	*C. thwaitesii*	Result	*C. rotang*	*C. thwaitesii*	Result
2	3.5880	4.2742	*ns*	1.7477	2.8833	*ns*
14	1.5689	2.2358	*ns*	1.4321	1.9484	*ns*
26	1.7017	1.1125	*ns*	1.7068	0.8797	*s*
38	1.9715	1.4941	*ns*	3.6976	1.6826	*s*

n= 5 replicates

5.2 RHIZOME DEVELOPMENT

Calamus is a clustering palm and the clustering was relatively close in the two species selected for study. Suckers produced from the very base of the parental axes extended laterally not more than 10 cm from the parental axes. The proximal lateral buds developed into suckers. *C. rotang* started clustering before *C. thwaitesii*.

Rhizome development started in the two species along with the development of multiple stems. Seedling leaves had vegetative buds in their axils. They grew out penetrating the supporting leaf sheaths splitting it into two at the base. These lateral suckers developed a root system at an early stage and thus became less dependent on the parent axis. The suckers developed repeated growth characteristics of the parent stem.

C. rotang and *C. thwaitesii* differed in the time of elongation of the primary stem. While primary shoot elongated before the production of suckers in *C. rotang*, 3-4 suckers were produced before the primary shoot elongation in *C. thwaitesii* (Fig. 23,24).

5.3 ROOT GROWTH IN RELATION TO SOIL PROPERTIES

A given edaphic environment is the result of a multitude of interactions between the many aspects of soil. Soil exploration and exploitation, which is a fundamental activity of the root system, has proved unamenable to quantitative investigation.

Plant growth is greatly decided by the nature and properties of soil in which it grows and the underground growth, especially the vertical and horizontal distribution of roots of *Calamus* is affected during the early growth stages. Hence an attempt was made to find out the growth of roots in relation to soil properties at different depths and radial distances. The results are summarized under the following headings.

1. Root growth as influenced by the variation in radial distance from the plant
2. Root growth as influenced by the variation in soil depth
3. Influence of soil properties on root growth

5.3.1 Root growth as influenced by variation in radial distance from the plant

The mean values of various root parameters viz., root length, total root weight, fine root weight and rooting density at different radial distances from the plant (0, 10 & 30 cm) were computed and is reported in Table 17.

Results revealed (Table 17.) that *C. rotang* attained the maximum values at the base of the plant for various root parameters viz., root length (43.45 cm), total root weight (0.92 g), fine root weight (0.08 g) and rooting density (0.23 cm cm^{-3}) within a soil depth of 0-60 cm, and there was a gradual decrease in root growth such as root length, total root weight, and rooting density with increase in the lateral distance. But this decrease in root growth with increase in radial distance was significant only in the case of total root weight. While 36 per cent and 37 per cent rooting density was present at a lateral distance of 0 cm and 10 cm respectively, 27 per cent was present at a lateral distance of 30 cm (calculated from Table 17).

When different soil layers were considered separately, as observed in 0-60 cm layer, in the surface layer (0-15 cm) also maximum mean values of various root parameters viz., root length (126.97 cm), total root weight (3.44 g) and rooting density (0.67 cm cm^{-3}) were obtained at the base of the plant and there was a decrease in root growth with increase in lateral distance as revealed in root length, total root weight and rooting density. Unlike in the surface layer, in most of the subsurface layers there was no decrease in root parameters with increase in radial distance. However, the soil at the two depths (15-30 cm and 30-45 cm) showed maximum rooting density at 10 cm away from the plant and minimum at the rhizosphere region.

Table 17. Mean values of root parameters at different radial distances and depths from the base of the plant.

Root Parameters	RD (cm)	*C. rotang*					*C. thwaitesii*				
		Depth (cm)					Depth (cm)				
		0-15	15-30	30-45	45-60	0-60	0-15	15-30	30-45	45-60	0-60
Root Length (cm)	0	126.97	18.70	16.19	11.94	43.45	189.39	76.06	7.07	14.77	71.82
	10	101.62	37.08	21.37	11.26	42.83	100.48	43.21	16.87	11.79	43.08
	30	75.69	20.95	20.02	9.31	31.49	91.61	32.58	10.56	23.10	39.46
	0-30	94.13	27.54	20.05	10.52		109.38	43.35	12.76	17.06	
Total root weight (g)	0	3.44	0.14	0.06	0.05	0.92	4.08	0.41	0.03	0.05	1.14
	10	1.14	0.25	0.14	0.10	0.41	0.44	0.19	0.11	0.03	0.19
	30	0.50	0.26	0.14	0.04	0.23	0.35	0.22	0.14	0.05	0.19
	0-30	1.19	0.24	0.13	0.06		0.92	0.23	0.11	0.04	
Fine root weight (g)	0	0.23	0.04	0.02	0.03	0.08	0.36	0.14	0.01	0.03	0.13
	10	0.23	0.04	0.03	0.01	0.08	0.20	0.08	0.03	0.03	0.08
	30	0.11	0.04	0.02	0.02	0.05	0.23	0.06	0.03	0.02	0.08
	0-30	0.18	0.04	0.02	0.02		0.23	0.08	0.03	0.02	
Rooting density (cm cm^{-3})	0	0.67	0.10	0.09	0.06	0.23	1.01	0.40	0.04	0.08	0.38
	10	0.54	0.20	0.11	0.06	0.23	0.53	0.23	0.09	0.06	0.23
	30	0.40	0.11	0.11	0.05	0.17	0.49	0.17	0.06	0.12	0.21
	0-30	0.50	0.15	0.10	0.06		0.58	0.23	0.07	0.09	

RD - Radial distance

n=5 Replicates

In C. *thwaitesii* also, the maximum mean values of various root parameters viz., root length (71.82 cm), total root weight (1.14 g), fine root weight (0.13 g) and rooting density (0.38 cm cm^{-3}) within a depth of 0-60 cm were achieved at the base of the plant. There was a decrease in the root growth with increase in the lateral distance and this decrease was significant in all the three. While 46 per cent of rooting density was present at the basal region of the plant within 60 cm depth, 29 per cent was found at 10 cm radial distance and 25 per cent at 30 cm radial distance(calculated from Table 17).

In the surface layer (0 -15 cm) also, maximum mean values of root parameters such as root length (189.39 cm), total root weight (4.08 g), fine root weight (0.36 g) and rooting density (1.01 cm cm^{-3}) were attained at the base of the plant and they decreased with increase in lateral distance. But such distinct trend was not seen at 30 – 45 cm and 45 – 60 cm soil depths. As in surface layer, in the subsurface layer (15-30 cm) also there was a gradual decrease in root growth with increase in the radial distance as revealed in root length, fine root weight and rooting density. Contrary to that of the surface layer, total root weight increased with increase in radial distance at 30-45 cm soil depth. However, at 15-30 cm soil depth, total root weight was found to be maximum at the base of the plant and minimum at a distance of 10 cm away from the plant. Soil at 30-45 cm depth showed a maximum rooting density at 10 cm away from the plant and minimum at the basal region.

In this study radial distance inversely affected the root growth in both the species especially within a soil depth of 0-60 cm rather than at different soil layers considered separately.

5.3.2 Root growth as influenced by the variation in the depth of soil

Mean values of different root parameters viz., root length, total root weight, fine root weight and rooting density at different soil depths (0-15 cm, 15-30 cm, 30-45 and 45-60 cm) were calculated and is given in Table 17.

In *C. rotang* maximum mean values for various root parameters (Table 17.) viz., root length (94.13 cm), total root weight (1.19 g), fine root weight (0.18 g) and rooting density (0.50 cm cm^{-3}) up to a radial distance of 30cm, were achieved at the surface layer (0-15 cm) of the soil.

In the basal part of the plant, maximum mean values of various root parameters viz., root length (126.97 cm), total root weight (3.44 g) and rooting density (0.67 cm cm^{-3}) were obtained at the surface layer and there was a significant decrease in them with increase in depth of soil. At a radial distance of 10 cm away from the plant, various root parameters viz., root length (101.62 cm), total root weight (1.14 g), fine root weight (0.23 g) and rooting density (0.54 cm cm^{-3}) were at their maximum at the surface layer and decreased with increase in depth. At a radial distance of 30 cm away from the plant the surface layer of the soil attained maximum mean values for various root parameters viz., root length (75.69 cm), total root weight (0.50 g), fine root weight (0.11 g) and rooting density (0.40 cm cm^{-3}). There was decrease in root growth with increasing depth as revealed by all the four root parameters.

In *C. thwaitesii* (Table 17) also, within a radius of 30 cm, maximum mean values for various root parameters viz., root length (109.38 cm), total root weight (0.93 g), fine root weight (0.23 g) and rooting density (0.58 cm cm^{-3}) were obtained at the surface layer (0-15 cm) and there was a significant decrease in total root weight and fine root weight with increase in soil depth.

At the basal region of the plant, the maximum mean values for various root parameters viz., root length (189.39 cm), total root weight (4.08 g), fine root weight (0.36 g) and rooting density (1.01 cm cm^{-3}) were attained at the surface layer and there was a decrease in all the root parameters in the immediate sub surface layer. At a radial distance of 10 cm away from the plant, the maximum mean values for various root parameters viz., root length (100.48 cm), total root weight (0.44 g), fine root weight (0.20 g) and rooting density (0.53 cm cm^{-3}) were highest at the surface layer and all of them showed a depth wise decrease. At 30 cm away from the plant also there was a gradual and significant decrease in total root weight and fine root weight with increase in soil depth. The maximum mean values of various root parameters viz., root length (91.61 cm), total root weight (0.35 g), fine root weight (0.23 g) and rooting density (0.49 cm cm^{-3}) were achieved at the surface layer at 30cm radial distance from the plant. In this study soil depth had an inverse effect on root growth.

5.3.3 Influence of soil parameters on root growth

Suitability of any vegetation to a particular soil is greatly controlled by the establishment and proliferation of root system in that soil which in turn is decided by the nature and properties of the soil. The growth and development of a root system can be evaluated using different root parameters like root length, rooting density, total root weight and fine root weight. Information in soil morphological, physical, chemical and biological properties give an idea about the nature of soil. So in this part of study an attempt was made to find out the growth and development of root system of two species of *Calamus* (*C. rotang* and *C. thwaitesii*) in relation to properties of soil.

Correlation coefficient between the various root parameters (root length, total root weight, fine root weight and rooting density) and soil properties (soil moisture, bulk density, gravel, sand, silt, clay, pH, organic carbon, exchangeable Ca and Mg, Na and K, exchangeable acidity, exchangeable aluminium, available N and extractable P) at different depths (0-15 cm, 15-30 cm, 30-45 cm, 45-60 cm) and at three distances from the base of the plant (0 cm, 10 cm, and 30 cm) were found out and the results obtained are furnished in Table 18, Table 19 and Table 20.

5.3.3.1 Physical properties

Physical condition of soil as indicated by various physical properties (Table 18) viz., soil moisture, gravel, sand, silt, clay and bulk density and their influence on the root growth are detailed bellow.

Soil moisture

In general, the mean content of soil moisture varied from 6.03 to 7.92 per cent in soil around *C. rotang* within a depth of 0-60 cm and up to a radial distance of 30 cm. In this volume of soil highly significant and negative relation of soil moisture with root parameters such as root length (r = -0.3040**), total root weight (r = -0.2894**), fine root weight (r = -0.3362**) and rooting density (r = -0.3007**) were observed. In soil around *C. thwaitesii,* comparatively higher content of soil moisture was recorded and it was found to have a highly significant and negative correlation with root length (r = -0.2285**) and rooting density (r = -0.2485**) (Table 18).

When different lateral distances were considered separately, influence of soil moisture on root growth was more pronounced at 10 cm away from the base of plant in *C. rotang*. Soil moisture showed highly significant and negative correlation with root length (r = -0.4106**), total root weight (r = -0.3894**), fine root weight (r = -0.4494**) and rooting density (r = -0.4099**) at this region. Significant negative correlation was shown by soil moisture with root length (r = -0.4828*), total root weight (r = -0.4926*), fine root weight (r = -0.4851*) and rooting density (r = -0.4834*) at the base of the plant in *C. rotang* (Table 21).

In *C. thwaitesii*, soil moisture significantly and negatively correlated with root length (r = -0.3206*), fine root weight (r = -0.2774*), and rooting density (r = -0.4191**) at a radial distance of 30 cm (Table 19).

Among the different depths, significant relation of soil moisture on root growth was more pronounced at 45- 60 cm depth in *C. rotang* and at 15 – 30 cm depth in *C. thwaiwtisii*. It was significantly and negatively correlated with rooting density (r = -0.4149*) at 45 – 60 cm soil depth in *C. rotang* and positively correlated with total root weight (r = 0.3524*) at 15 – 30 cm soil depth in *C. thwaitesii* (Table 20).

Gravel

Results revealed a relatively higher content of gravel in soil around *C. thwaitesii* (32.23 % - 41.65 %) than that of *C. rotang* (24.57 % - 39.81 %) within a depth of 0-60 cm and up to a radial distance of 30 cm. In this volume of soil highly significant and negative relation of gravel with root parameters such as root length (r = -0.3279**) , total root weight (r = -0.2553**), fine root weight (r = -0.3656**), and rooting density (r = -0.3204**) was observed in *C. rotang*. Similar relation with all the root parameters viz., root length (r = -0.5608**), total root weight (r = -0.2393**), fine root weight (r = -0.3949**), and rooting density (r = -0.5221**) was observed in *C. thwaitesii* also (Table 18).

At a lateral distance of 10 cm from basal region of the plant, gravel had significant and negative relationship with root length (r = -0.4406**, -0.5277**), total root weight (r = -0.3206*, -0.4379**), fine root weight (r = -0.4771**, -0.4820**) and rooting density (r = -0.4339**, -0.5089**) in *C. rotang* and *C. thwaitesii* respectively. Both, *C. rotang* and *C. thwaitesii* had highly significant and negative correlation for gravel with root length (r = -0.5790**, -0.6168**) and fine root weight (r = -0.5674**, -0.6726**) at the base of the plant. Total root weight and rooting density at the base of the plant (r = -0.5120*, -0.5572*) were also influenced by gravel in *C. rotang*. In *C. thwaitesii* gravel showed significant negative correlation with root length (r = -0.6607**), fine root weight (r = -0.2759*) and positive correlation with rooting density (r = 0.5465**) at 30 cm radial distance (Table 19).

On considering different soil depths, significant and negative correlation of gravel with total root weight (r = -0.3565*) at 30 – 45 cm depth was seen in *C. rotang*. In *C. thwaitesii*, the influence of gravel was more pronounced on root length (r = -0.5485**, -0.3975*) at 0 –1 5 cm and 15 – 30 cm respectively. It also correlated significantly and negatively with rooting density (r = -0.4237*, -0.3986*) at 0 –15 cm and 15 – 30 cm respectively (Table 20).

Texture

Mean content of sand in the soil around *C. rotang* varied from 29.8 per cent to 44.2 per cent while that in *C. thwaitesii* varied from 29 per cent to 46.8 per cent. Soil around *C. thwaitesii* was also found to have a higher content of silt (r = 20 per cent to 44.6 per cent) when compared to the soil around *C. rotang* (r = 19.6 per cent to 37.6 per cent).

Among the soil separates, sand was found to have a highly significant and positive relation with all the root parameters such as as root length (r = 0.4530**, 0.4450**) , total root weight (r = 0.3931**, 0.2497**), fine root weight (r = 0.3383**, 0.4886**), and rooting density (r = 0.4446**, 0.4217**) in both *C. rotang* and *C thwaitesii* respectively. Silt was found to exert significant and negative impact on root length (r = -0.1945*), total root weight (r = -0.2522**), and rooting density (r = -0.1850**) in *C. rotang* while in *C. thwaitesii* its influence was noticed on root length (r = -0.2222**), fine root weight (r = -0.2725**) and rooting density (r = -0.2114*). But in the case of clay no such significant relation with any of the root parameters was observed in both the species (Table 18).

Sand had more pronounced influence on root growth at 10 cm away from the plant in both the species. Highly significant and positive relation of sand with root length (r = 0.5655**,

0.6164^{**}), total root weight (r = 0.5213^{**}, 0.5862^{**}), fine root weight (r = 0.4468^{**}, 0.6375^{**}) and rooting density (r = 0.5549^{**}, 0.6151^{**}) was noticed at this region in both *C. rotang* and *C. thwaitesii* respectively (Table 19).

Correlation coefficient between root parameters and soil properties at different soil depths revealed a significant and negative relationship for sand with fine root weight (r = -0.3814^{*}) at 15 – 30 cm depth in *C. rotang* while highly significant and positive relationship for sand with total root weight (r = 0.4335^{**}) and fine root weight (r = 0.5400^{**}) at 30 – 45 cm depth was found in *C. thwaitesii* (Table 20).

Table 18. Correlation between soil physical properties and root parameters within a depth of 0- 60 cm and up to a radial distance of 30 cm.

Soil properties	*C. rotang*				*C. thwaitesii*			
	Root parameters				Root parameters			
	RL	TRW	FRW	ROD	RL	TRW	FRW	ROD
S.moisture	-0.3040^{**}	-0.2894^{**}	-0.3362^{**}	-0.3007^{**}	-0.2285^{**}	-0.1282	-0.1126	-0.2485^{**}
Bulk density	-0.0996	-0.1853^{*}	-0.1595	-0.1158	-0.1321	-0.1057	-0.1059	-0.1557
Gravel	-0.3279^{**}	-0.2553^{**}	-0.3656^{**}	-0.3204^{**}	-0.5608^{**}	-0.2393^{**}	-0.3949^{**}	-0.5221^{**}
Sand	0.4530^{**}	0.3931^{**}	-0.3383^{**}	0.4446^{**}	0.4450^{**}	0.2497^{**}	0.4886^{**}	0.4217^{**}
Silt	-0.1945^{*}	-0.2522^{**}	-0.1463	-0.1850^{*}	0.2222^{**}	-0.1067	-0.2725^{**}	-0.2114^{*}
Clay	-0.1369	-0.0187	-0.1097	-0.142	-0.0517	-0.0346	-0.0396	-0.048

RL - Root length TRW - Total root weight FRW - Fine root weight ROD - Rooting density

* - Significant at 5 %, ** - Significant at 1 %

Table 19. Correlation between soil physical properties and root parameters at different distances from the base of the plant.

Distance from the base of the plant (cm)	Soil physical properties	*C. rotang*				*C. thwaitesii*			
		Root parameters				Root parameters			
		RL	TRW	FRW	ROD	RL	TRW	FRW	ROD
0	Moisture	-0.4828*	-0.4926*	-0.4851*	-0.4834*	-0.2881	-0.3893	-0.0087	-0.2873
	Bulk density	-0.3273	-0.3855	-0.3092	-0.3130	-0.4491*	-0.1601	-0.1524	-0.4481
	Gravel	-0.5790**	-0.5120*	-0.5674**	-0.5572*	-0.6168**	-0.3643	-0.6726**	-0.6173
	Sand	0.5123*	0.4570*	0.3455	0.4769*	0.5096*	0.4464*	0.6612**	0.5101*
	Silt	-0.3597	-0.3444	-0.2599	-0.3256	0.4056	-0.1622	-0.4531*	-0.4064
	Clay	0.0408	0.0681	0.0516	0.0259	0.1545	-0.0761	0.0065	0.5130
10cm	Moisture	-0.4106**	-0.3894**	-0.4494**	-0.4099**	-0.2288	-0.2121	-0.0923	-0.2272
	Bulk density	-0.2397	-0.3077*	-0.2794*	-0.2571*	-0.0254	-0.0810	-0.0997	-0.0310
	Gravel	-0.4406**	-0.3206*	-0.4771**	-0.4339**	-0.5277**	-0.4379**	-0.4820**	-0.5089**
	Sand	0.5655**	0.5213**	0.4468**	0.5549**	0.6164**	0.5862**	0.6375**	0.6151**
	Silt	-0.2155	-0.2605	-0.1343	-0.2150	-0.2235	-0.0905	-0.2563	-0.2091
	Clay	-0.1697	-0.0830	-0.1768	-0.1623	-0.0156	-0.1503	0.0117	-0.0311
30 cm	Moisture	-0.1104	-0.0510	-0.0947	-0.1063	-0.3206*	-0.0434	-0.2774*	-0.4191**
	Bulk density	0.1392	0.0689	0.0811	0.1063	-0.0769	-0.1738	-0.0963	-0.1374
	Gravel	-0.1498	-0.1865	-0.1869	-0.1441	-0.6607**	-0.3152*	-0.2759*	0.5465**
	Sand	0.3297*	0.4069**	0.2309	0.3357**	0.4284**	0.3161*	0.4285**	0.3619**
	Silt	0.0173	-0.1673*	0.0813	0.0292	-0.1006	-0.1416	-0.2251	0.0922
	Clay	-0.3665**	-0.2163	-0.3782**	-0.3887**	-0.3108*	-0.1407	-0.1472	-0.2529

RL - Root length   TRW - Total root weight   FRW - Fine root weight   ROD - Rooting density

* - Significant at 5 %, ** - Significant at 1 %

Table 20. Correlation between soil physical properties on root parameters at different soil depths

Depth (cm)	Soil physical properties	*C. rotang*				*C. thwaitesii*			
		Root parameters				Root parameters			
		RL	TRW	FRW	ROD	RL	TRW	FRW	ROD
0-15	Moisture	-0.1007	-0.2751	-0.2263	-0.0880	-0.0539	-0.0458	0.1154	-0.0907
	Bulk density	-0.0013	-0.3200	-0.2346	0.0224	-0.0462	-0.1249	0.0448	-0.5420
	Gravel	-0.1774	-0.1384	0.2583	-0.1674	-0.5485**	-0.0573	-0.2197	-0.4237*
	Sand	0.1169	0.1778	-0.0399	-0.0807	0.1136	-0.0266	0.2923	-0.1394
	Silt	-0.1195	-0.2859	-0.0899	-0.0852	-0.3054	-0.0105	-0.3931*	-0.0890
	Clay	0.0653	0.2443	0.1596	0.0488	0.2605	0.0855	0.1314	0.2462
15-30	Moisture	0.0978	0.3201	-0.0859	-0.0898	0.0764	0.3524*	0.1806	0.0761
	Bulk density	-0.0105	-0.2137	0.0877	-0.0501	-0.0122	0.1839	0.0669	-0.0135
	Gravel	0.0526	0.1855	-0.1157	0.1288	-0.3975*	-0.3119	-0.3192	-0.3986*
	Sand	0.1398	0.2961	-0.3814*	0.0904	0.0566	0.2105	0.2519	0.0588
	Silt	-0.1220	-0.1306	0.3567*	-0.0517	0.0701	0.1501	0.0422	0.0716
	Clay	0.0756	-0.0385	-0.2292	-0.0094	-0.0933	-0.2361	-0.1450	-0.0956
30-45	Moisture	-0.1737	-0.2372	-0.0029	-0.1514	0.0220	-0.0954	-0.2597	0.0627
	Bulk density	0.3722*	0.3439*	-0.0047	0.2393	-0.2489	-0.5395**	-0.5353**	-0.2543
	Gravel	0.2520	-0.3565*	0.2628	0.2821	-0.1981	-0.1256	-0.2049	-0.2107
	Sand	0.1578	-0.1484	-0.0672	0.1395	0.3077	0.4335**	0.5400**	0.3077
	Silt	0.1154	-0.2183	-0.1352	0.1102	-0.0428	-0.2042	-0.3170	-0.0428
	Clay	-0.1552	0.1334	0.0661	-0.1374	0.1102	0.0246	0.1090	-0.1124
45-60	Moisture	0.0269	-0.1494	-0.2789	-0.4149*	0.1100	-0.0716	-0.0971	-0.1180
	Bulk density	-0.0424	-0.0329	0.2294	0.0629	-0.0882	-0.0716	-0.1634	-0.2566
	Gravel	-0.0883	0.0227	0.0105	-0.0806	-0.2668	-0.0977	-0.1253	-0.1105
	Sand	-0.0767	0.1017	0.1200	-0.0261	-0.0561	0.1316	0.1538	0.0482
	Silt	0.0555	-0.3146	-0.1345	-0.0034	0.1398	0.0349	-0.0181	0.0570
	Clay	-0.0081	0.2820	0.0663	0.0224	-0.1536	-0.1733	-0.1160	-0.1285

RL - Root length TRW - Total root weight FRW - Fine root weight ROD - Rooting density

* - Significant at 5 %, ** - Significant at 1 %

Bulk density

A relatively higher bulk density at a depth from 0-60 cm and a radial distance from 0-30 cm was observed in the soil around *C. thwaitesii* (1.57 gcm^{-3}) than that around *C. rotang* (1.51 gcm^{-3}). The rhizosphere of *C. thwaitesii* was more compact than *C. rotang* as evidenced by the higher values of bulk density. The significant and negative influence of bulk density on root growth was observed only in the case of total root weight ($r = -0.1853^{*}$) in *C. rotang* and no significant relation was observed with any of the root parameters in the case of *C. thwaitesii* (Table 18).

Different lateral distances when considered separately, showed that influence of bulk density on root growth was comparatively more in *C. rotang* than in *C. thwaitesii* at a distance of 10 cm from the plant. While in *C. rotang* there was a significant and negative influence on total root weight ($r = -0.3077^{*}$), fine root weight ($r = -0.2794^{*}$) and rooting density ($r = -0.2571^{*}$) at 10 cm away from the plant, in *C. thwaitesii,* significant and negative relation ship for bulk density with root length ($r = -0.4491^{*}$) alone was noted immediately at the base of the plant (Table 19).

Significant relation between bulk density and root growth was noted only at 30 – 45 cm soil depth in *C. rotang* and *C. thwaitesii.* At this depth there existed a significant and positive correlation for bulk density with root length and total root weight in *C. rotang*. In *C. thwaitesii*, highly significant and negative relationship for bulk density with total root weight and fine root weight was noticed at the same depth (Table 20).

5.3.3.2 Chemical properties

In order to find out the proliferation of *Calamus* roots in relation to the chemical nature of soil, various soil properties (pH, organic carbon, available N, extractable P, exchangeable Al, exchange acidity and exchangeable bases) and various root parameters such as root length, total root weight, fine root weight and rooting density were determined at different depths (0-15, 15-30, 30-45, and 45 –60 cm), and radial distances (0, 10 and 30 cm) and their correlation coefficient were found out.

pH

The mean values of soil pH in *C. rotang* varied from 5.04 to 5.22 and it ranged from 4.53 to 4.74 in *C. thwaitesii.* This showed that soils surrounding *C. thwaitesii* were more acidic than that of *C. rotang.*

At 30 cm away from the base of the plant pH showed significant and positive relation with total root weight in *C. rotang* (0.2879*). But no such relation existed for soil pH on root growth in *C. thwaitesii* at different lateral distances studied (Table 22).

Most of the root parameters were not found affected by the pH of soil in *C. rotang* at any of the depths. However, there was highly significant and negative relation for pH with total root weight (r = -0.4696**) at 30-45 cm depth. In *C. thwaitesii,* root length (r = 0.4630**, 0.3410*) and rooting density (r = 0.4629**, 0.3413**) was significantly and positively affected by pH at 0 –15 cm and 15 - 30 cm respectively (Table 23).

Organic carbon

Mean content of OC in soil surrounding *C. rotang* ranged form 0.52 to 1.77 per cent while that of *C. thwaitesii* varied from 0.55 to 1.93 per cent.

Within a depth of 0 - 60 cm and a radial distance of 30 cm, root growth was highly influenced by the content of organic carbon which was revealed by its highly significant and positive relation with root length (r = 0.5469**, 0.5661**) , total root weight (r = 0.3663**, 0.2013*), fine root weight (r = 0.5585**, 0.5289**) and rooting density (r = 0.5546**, 0.6044**) in *C. rotang* and *C. thwaitesii* respectively (Table 21).

Organic carbon at different lateral distance from the base of the plant showed positive correlation with the different root parameters. At the base of the plant it showed significant and positive correlation with root length (r = 0.5654**, 0.6355**), fine root weight (r = 0.5916**, 0.7269**) and rooting density (r = 0.5645*, 0.5353*) in *C. rotang* and *C. thwaitesii* respectively. Organic carbon at the immediate base of *C. rotang,* un like in *C. thwaitesii,* showed positive correlation with total root weight (r = 0.5686**). At a distance of 10 cm away from the basal region of the plant organic carbon showed highly significant and positive correlation with root length (r = 0.6495**, 0.6113**), total root weight (r = 0.5723**, 0.5289**), fine root weight (r = 0.6528**, 0.5878**) and rooting density (r = 0.6454**, 0.6365**) in *C. rotang* and *C. thwaitesii* respectively. Organic carbon, at 30 cm away from the plant showed significant and positive correlation with root length (r = 0.4675**, 0.6194**), total root weight (r = 0.2861*, 0.4350**), fine root weight (r = 0.4920**, 0.5023**) and rooting density (r = 0.4865**, 0.6863**) in *C. rotang* and *C. thwaitesii* respectively (Table 22).

In the subsurface layer (30 - 45 cm), significant and negative impact of organic carbon on root length (r = -0.3683*) and rooting density (r = -0.3807*) was seen in *C. rotang.* But root growth was significantly and positively related to organic carbon at 30 – 45 cm depth and 45 – 60 cm soil depth in *C. thwaitesii.* Among the root parameters studied in this species, total root weight and fine root weight (r = 0.4091*, 0.4811**) were predominant at 30 – 45 cm depth and fine root weight (r = 0.4710**) and rooting density (r = 0.4364**) were predominant at 45 - 60 cm depth. (Table 23).

Available N

The mean content available N in soil ranged from of 0.04 to 0.07 per cent in *C. rotang* and 0.04 to 0.07 per cent in *C. thwaitesii.*

As in the case of organic carbon, within a depth of 0-60 cm and a radial distance of 30 cm, root growth was highly influenced by the content of available N in soil . This was revealed by the significant and positive relation between available N and root parameters such as root length ($r = 0.3243^{**}$, 0.3045^{**}), fine root weight ($r = 0.2256^{**}$, 0.2015^{*}) and rooting density ($r = 0.3326^{**}$, 0.3012^{**}) in *C. rotang* and *C. thwaitesii* respectively. In *C. rotang*, available N was positively correlated with total root weight ($r = 0.1866^{*}$) also (Table 21).

On considering different lateral distances, the influence of available N on root growth was found to be more at 10 cm away from the base of the plant in both the species of rattans. A significant and positive relation existed between available N and root length ($r = 0.4463^{**}$, 0.3971^{**}), total root weight ($r = 0.4081^{**}$, 0.2629^{*}), fine root weight ($r = 0.3309^{*}$, 0.3886^{**}) and rooting density ($r = 0.4407^{**}$, 0.3964^{**}) in *C. rotang* and *C. thwaitesii* respectively at 10 cm away from the plant. At a lateral distance of 30 cm, available N had significant and positive relation with root length ($r = 0.3704^{**}$, 0.3103^{*}) and rooting density ($r = 0.3870^{**}$, 0.3109^{**}) in *C. rotang* and *C. thwaitesii* respectively. In addition, significant and positive relation was also noted with fine root weight ($r = 0.3559^{**}$) in *C. rotang*. Available N in the soil immediately beneath the base of the plant had no influence on root growth in *C. rotang* while a significant positive relation was noted with root length ($r = 0.5554^{*}$) and rooting density ($r = 0.5549^{*}$) in *C. thwaitesii* (Table 22).

In *C. rotang* both at surface ($r = -0.4066^{*}$) and 45 - 60 cm depths ($r = -0.4066^{*}$), available N was found to exert significant and negative impact on fine root weight. In *C thwaitesii*, at 0 - 15 cm depth, significant and negative influence on total root weight ($r = -0.0313^{**}$) was noticed. At 30 – 45 cm depth there existed significant and positive influence on root length ($r = 0.5368^{**}$) and rooting density ($r = 0.5548^{**}$) in this species (Table 23).

Extractable P

When the root growth within a depth of 0-60 cm and a radial distance of 30 cm were taken into consideration , extractable P was found to have highly significant and positive influence on most of the root parameters viz., with root length (r = 0.2375**), fine root weight (r = 0.2462**) and rooting density (r = 0.2385**) in *C. rotang.* But the significant and positive influence of extractable P was expressed only by the fine root weight (r = 0.2183*) in *C. thwaitesii* (Table 21).

Table 21. Correlation between soil chemical properties (soil reaction and nutrients) and root growth within a depth of 0- 60 cm and up to a radial distance of 30 cm.

Soil propertie	*C. rotang*				*C. thwaitesii*			
	Root parameters				Root parameters			
	RL	TRW	FRW	ROD	RL	TRW	FRW	ROD
pH	0.0721	0.0926	0.0537	0.0737	0.11	0.0642	0.0295	0.0702
OC	0.5469**	0.3663**	0.5585**	0.5546**	0.5661**	0.2013*	0.5289**	0.6044**
Av N	0.3243**	0.1866*	0.2256**	0.3326**	0.3045**	0.0908	0.2015*	0.3012**
Extr. P	0.2375**	0.0984	0.2462**	0.2385**	0.1508	0.0525	0.2183*	0.114

RL - Root length TRW - Total root weight FRW - Fine root weight ROD - Rooting density
OC - Organic Carbon Av. N – Available Nitrogen Extr. P - Extractable Phosphorous
* - Significant at 5 %, ** - Significant at 1 %

With respect to the different lateral distances, influence of extractable P on root growth was predominant at 30 cm away from the plant in both species. Highly significant positive relation was noted for extractable P at this lateral distance with root length (r = 0.3433**), fine root weight (r = 0.3364^{**}) and rooting density (r = 0.3498^{**}) in *C. rotang*. However in *C. thwaitesii*, there was significant positive relation for extractable P with root length (r = 0.3215^{*}) and fine root weight (r = 0.4145^{**}) alone. In this species, extractable P exercised a significant and positive influence with total root weight (r = 0.2813^{*}) at 10 cm lateral distance also (Table 22.).

Table 22. Correlation between soil chemical properties (soil reaction and nutrients) and root growth at different distances from the base of the plant

Distance from the base of the plant (cm)	Soil properties	*C. rotang*				*C. thwaitesii*			
		Root parameters				Root parameters			
		RL	TRW	FRW	ROD	RL	TRW	FRW	ROD
0	pH	0.1648	0.1487	0.1113	0.1796	0.1851	0.0672	0.1723	0.1843
	OC	0.5654^{**}	0.5686^{**}	0.5916^{**}	0.5645^{*}	0.6355^{**}	0.3147	0.7269^{**}	0.5353^{**}
	Av. N	0.2	0.2056	0.0449	0.2128	0.5554^{*}	0.426	0.3258	0.5549^{*}
	Extr. P	0.1299	0.1397	0.2621	0.117	-0.1474	0.0925	-0.0232	-0.147
10 cm	pH	0.055	-0.02	0.0934	0.0584	0.1503	-0.042	0.161	0.1369
	OC	0.6495^{**}	0.5723^{**}	0.6528^{**}	0.6454^{**}	0.6113^{**}	0.5289^{**}	0.5878^{**}	0.6365^{**}
	Av. N	0.4463^{**}	0.4081^{**}	0.3309^{*}	0.4407^{**}	0.3971^{**}	0.2629^{*}	0.3886^{**}	0.3964^{**}
	Extr. P	0.2175	0.1452	0.2292	0.2123	0.2382	0.2813^{*}	0.199	0.2386
30 cm	pH	0.0281	0.2879^{*}	-0.0821	0.0202	-0.069	-0.0167	-0.2194	-0.1581
	OC	0.4675^{**}	0.2861^{*}	0.4920^{**}	0.4865^{**}	0.6194^{**}	0.4350^{**}	0.5023^{**}	0.6863^{**}
	Av.N	0.3704^{**}	0.2221	0.3559^{**}	0.3870^{**}	0.3103^{*}	0.065	0.1135	0.3109^{*}
	Extr. P	0.3433^{**}	0.1918	0.3364^{**}	0.3498^{**}	0.3215^{*}	0.1054	0.4145^{**}	0.1975

RL - Root length TRW - Total root weight FRW - Fine root weight ROD - Rooting density

OC - Organic Carbon Av. N – Available Nitrogen Extr. P - Extractable Phosphorous

* - Significant at 5 %, ** - Significant at 1 %

In *C. rotang,* root growth was not found affected by extractable P content of soil at any of the depths studied. But in *C. thwaitesii,* it was found to exert a highly significant and positive impact at 15-30 cm depth on root length (r = 0.5314**), total root weight (r = 0.4913**), fine root weight (r = 0.6017**) and rooting density (r = 0.5371**) (Table 23).

Table 23. Correlation between soil chemical properties (soil reaction and nutrients) on root growth at different soil depths.

Depth (cm)	Soil properties	*C. rotang*				*C. thwaitesii*			
		Root parameters				Root parameters			
		RL	TRW	FRW	ROD	RL	TRW	FRW	ROD
0 –15	pH	0.2453	0.1325	0.0533	0.2625	0.4630**	0.2403	0.1588	0.4629**
	OC	0.0509	-0.2223	0.2815	0.068	-0.0401	-0.4337	0.2061	-0.0994
	Av.N	-0.3046	-0.2523	-0.4066*	-0.289	0.219	-0.0313**	0.0658	0.192
	Extr. P	-0.1924	-0.2549	-0.0762	-0.1821	-0.2703	-0.0948	0.1257	-0.3242
15 - 30	pH	-0.0864	0.0449	-0.0231	-0.0932	0.3410*	0.2268	0.1734	0.3413*
	OC	0.1464	0.3059	0.0387	0.1529	0.2849	0.2066	0.3273	0.285
	Av.N	0.2205	0.0436	-0.0052	0.2326	0.1909	0.252	0.2114	0.1947
	Extr. P	0.0131	0.0974	-0.0688	0.0067	0.5314**	0.4913**	0.6017**	0.5371**
30 – 45	pH	-0.0267	-0.4696**	-0.1313	-0.0688	0.2369	0.0146	0.1448	0.2237
	OC	-0.3683*	-0.1792	-0.0406	-0.3807*	0.2819	0.4091*	0.4811**	0.2911
	Av.N	-0.1762	-0.1604	-0.0049	-0.2045	0.5368**	0.31	0.209	0.5548**
	Extr. P	0.0433	0.0999	0.212	0.0118	0.0055	-0.0485	-0.0242	0.0035
40 - 60	pH	0.0189	0.1117	0.3066	0.0771	0.3314	0.992	0.2176	0.2766
	0c	-0.0035	0.0125	-0.1312	0.0106	0.2291	0.3273	0.4710**	0.4364**
	Av.N_2	-0.3046	-0.2523	-0.4066*	-0.1106	-0.0494	-0.0785	0.09	0.1499
	Av.P	-0.1924	-0.2549	-0.0762	-0.2268	0.2643	-0.1266	-0.0018	-0.0494

RL - Root length TRW - Total root weight FRW - Fine root weight ROD - Rooting density

OC - Organic Carbon Av. N – Available Nitrogen Extr. P Extractable Phosphorous

* - Significant at 5 %, ** - Significant at 1 %

Exchange acidity

Higher content of exchange acidity (0.098 to 0.370 meq/100g) was observed in the soil surrounding *C. rotang* when compared to that of *C. thwaitesii* (0.080 to 0.303 meq/100g).

Within a depth of 0-60 cm and a radius of 30 cm, root growth was not affected by exchange acidity of soil in *C. rotang*. But in *C. thwaitesii* significant and positive impact was noticed on root length (r = 0.2654**), fine root weight (r = 0.1781*) and rooting density (r = 0.2819**) (Table 24).

When the influences of exchange acidity at different lateral distances were considered, at 10 cm radial distance, it was significantly and positively correlated with root length (r = 0.2858*), fine root weight (r = 0.2993*) and rooting density (r = 0.2887*) in *C. thwaitesii*. It was also significantly and positively correlated with fine root weight (r = 0.3292*) in *C. rotang* and with root length (r = 0.3572**) and rooting density (r = 0.3878**) in *C. thwaitesii* at 30 cm radial distance (Table 25).

When different depths were considered separately, it was found to have no influence on any of the root parameters in *C. rotang*. But in *C. thwaitesii* significant and positive influence on total root weight (r = 0.4674**) and fine root weight (r = 0.3777*) was observed at 30 - 45 cm depths (Table 26).

Exchangeable Al

Exchangeable Al present in the soil was greater in *C. rotang* (0.030 to 0.340 meq/100 g) when compared to that of *C. thwaitesii* (0.037 to 0.257 meq/100 g).

As in the case of exchange acidity, root growth was not affected by exchangeable Al in *C. rotang* within a depth of 0-60 cm and 30 cm radius. On the contrary, both root length (r = 0.2284**) and rooting density (r = 0.2514**) was significantly and positively related to exchangeable Al in *C. thwaitesii* (Table 24).

At different lateral distances also there was no influence of exchangeable Al on root growth in *C rotang.* But in *C. thwaitesii,* its postive and significant impact was noticed on root length (r = 0.2647*) , total root weight (r = 0.2589*) and rooting density (r = 0.3176*) at 30 cm radial distance (Table 27).

None of the root parameters were seen to be influenced by exchangeable Al in the two species when different depths were taken into consideration (Table 26).

Exchangeable K

The mean content of exchangeable K in the soil varied from 74.76 to 107.9 ppm in *C. rotang* while in *C. thwaitesii* it was 62.93 to 211.5 ppm.

Significant influence of K on root growth within a depth of 0-60 cm and radius of 30 cm was noticed only in *C. thwaitesii.* All the root parameters such as as root length (r = 0.6352**) , total root weight (r = 0.5184**), fine root weight (r = 0.5945**), and rooting density (r = 0.6687**) were positively correlated with K (Table 24).

Potassium was found to have no influence on root growth at any of the lateral distances in *C. rotang* while in *C. thwaitesii* it was significantly and positively correlated with root growth at all the radial distances. The correlation coefficient was highly significant and positive between K and root parameters viz., root length (r = 0.7647**, 0.5524**, 0.5468**), total root weight (r = 0.7322**, 0.4529**, 0.4119**), fine root weight (r = 0.6931**, .04928**, 0.5915**), and rooting density (r = 0.7643**, 0.5893**, 0.6206**) at the base of the plant, at 10 cm and 30 cm away from the base of the plant respectively in *C. thwaitesii* (Table 25).

When different depths were considered separately, significant and positive correlation of K with most of the root parameters such as root length (r = 0.4133**), fine root weight (r = 0.3658*) and rooting density (r = 0.4512**) was observed at 45-60 cm depth in *C. rotang*. In *C. thwaitesii* its positive impact on total root weight (r = 0.5352**) and fine root weight (r = 0.5310**) were prevalent at 15-30 cm layer, in addition to its relation with total root weight (r = 0.3404**) at 45-60 cm depth (Table 26).

Exchangeable Na

Relatively higher content of exchangeable Na (43.46 to 71.2 ppm) was noticed in the soil surrounding *C. rotang*, when compared with *C. thwaitesii* (40.13 to 46.1 ppm).

Exchangeable Na had no influence on root growth in both the species of *Calamus* within a depth of 60 cm and a radius of 30 cm.

When different radial distances were considered separately, root growth was not correlated with Na at any of the radial distance in *C. rotang* while in *C. thwaitesii* at 30cm radial distance, exchangeable sodium was found significantly and negatively correlated with total root weight (r = 0.2632*) (Table 24).

In *C. rotang,* Na was found to exert significant and positive correlation with root parameters viz., total root weight (r = 0.3498*) in the surface layer and on root length (r = 0.3564*), fine root weight (r = 0.3474*) and rooting density (r = 0.3838*) at 45-60 cm depth. But in *C. thwaitesii* no such significant correlation was observed in any of the root parameters (Table 26).

Table 24. Correlation between soil chemical properties (exchange characteristics) and root growth within a depth of 0- 60 cm and up to a radial distance of 30 cm.

Soil properties	*C. rotang*				*C. thwaitesii*			
	Root parameters				Root parameters			
	RL	TRW	FRW	ROD	RL	TRW	FRW	ROD
Ex. acidity	0.0898	0.0612	0.0827	0.0939	0.2654^{**}	0.0226	0.1781^{*}	0.2819^{**}
Ex. Al	-0.0477	-0.0419	-0.0354	-0.0464	0.2284^{**}	0.0438	0.1605	0.2514^{**}
Ca	0.2172^{*}	0.0434^{*}	0.2166^{*}	0.2272^{**}	0.0055	0.0155	0.0015	-0.0054
Mg	0.0730	0.0722	-0.0018	-0.1232	0.0183	0.0331	-0.0574	-0.0065
Na	0.0325	0.0732	0.0583	-0.1493	-0.0656	-0.0598	-0.0321	-0.1102
K	-0.0217	0.1194	0.0006	-0.0219	0.6352^{**}	0.5184^{**}	0.5945^{**}	0.6687^{**}

RL - Root length TRW - Total root weight FRW - Fine root weight ROD - Rooting density
Ex. Al – Exchangeable Aluminium

* - Significant at 5 %, ** - Significant at 1 %

Exchangeable Ca

Soils of both the species of *Calamus* had almost the same content of exchangeable Ca. Mean value of Ca varied from 0.04 to 0.05 per cent in *C. rotang* while in *C. thwaitesii*, it varied from 0.04 to 0.05 per cent.

Contrary to K, influence of Ca within a depth of 0-60 cm and radius of 30 cm was pronounced only in *C. rotang* and all the root parameters viz., root length (r = 0.2172^{*}), total root weight (r = 0.0434*), fine root weight (r = 0.2166**), and rooting density (r = 0.2272**) were positively correlated with Ca (Table 24).

Table 25. Correlation between soil chemical properties (exchange characteristics) and root growth at different distances from the base of the plant

Distance from the base of the plant (cm)	Soil chemical properties	*C. rotang*				*C. thwaitesii*			
		Root parameter				Root parameter			
		RL	TRW	FRW	ROD	RL	TRW	FRW	ROD
0	Ex. acidity	0.0192	0.077	0.0369	0.0058	0.3224	0.0002	0.0791	0.3226
	Ex. Al	-0.0731	-0.0524	-0.0196	-0.0597	0.3169	0.0125	0.0712	0.3174
	Ca	-0.1589	-0.1433	0.0322	-0.0984	-0.2652	-0.2129	-0.2011	-0.2637
	Mg	0.3215	0.3284	0.2621	0.3273	-0.1944	-0.13	-0.2296	-0.1969
	Na	0.0001	-0.0311	0.0328	0.0173	-0.1062	-0.0882	-0.0742	-0.106
	K	0.0649	0.1162	0.2381	0.0957	0.7647**	0.7322**	0.6931**	0.7643**
10 cm	Ex. acidity	-0.005	0.048	-0.0028	0.0035	0.2858*	0.2428	0.2993*	0.2887*
	Ex. Al	-0.0124	0.043	0.0156	-0.009	0.2364	0.1587	0.2435	0.2401
	Ca	0.3286*	0.2258	0.3166*	0.3236*	0.0667	0.1085	0.028	0.0511
	Mg	-0.0278	-0.0543	-0.0602	-0.027	0.1138	-0.0933	0.0778	0.1078
	Na	-0.0643	-0.0812	0.0213	-0.0576	-0.1227	-0.2344	-0.127	-0.1443
	K	0.0444	0.1929	-0.0164	0.41	0.5524**	0.4529**	0.4928**	0.5893**
30 cm	Ex. acidity	0.2303	0.0482	0.3292*	0.2401	0.3572**	0.2378	0.2202	0.3878**
	Ex. Al	-0.0577	-0.0749	-0.0452	-0.0551	0.2647*	0.2589*	0.1994	0.3176*
	Ca	0.2828*	0.2147	0.2123	0.2749*	0.0907	0.3200*	0.0901	0.058
	Mg	0.1606	0.3292*	0.0408	0.1626	-0.1307	-0.2557*	-0.1417	-0.1839
	Na	0.1232	0.1636	0.0666	0.1224	-0.0379	-0.2632*	0.0439	-0.1629
	K	-0.197	-0.0958	-0.1874	-0.2024	0.5468**	0.4119**	0.5915**	0.6206**

RL - Root length TRW - Total root weight FRW - Fine root weight ROD - Rooting density

Ex. Al – Exchangeable Aluminium

* - Significant at 5 %, ** - Significant at 1 %

Table 26. Correlation between soil chemical properties (exchange characteristics) and root growth at different soil depths and radial distances.

Depths (cm)	Soil chemical properties	*C. rotang*				*C. thwaitesii*			
		Root parameter				Root parameter			
		RL	TRW	FRW	ROD	RL	TRW	FRW	ROD
0 –15	Ex. acidity	-0.1244	-0.1264	-0.1357	-0.1381	0.2262	-0.2176	0.0686	0.2585
	Ex. Al	-0.2327	-0.2974	-0.1499	-0.2223	0.2819	-0.1041	0.102	0.287
	Ca	0.3789*	-0.0927	0.2754	0.4329**	-0.0818	-0.0742	-0.1441	-0.1744
	Mg	0.0097	0.1134	-0.1206	0.0171	0.2866	-0.1906	0.0692	0.2883
	Na	0.1647	0.3498*	0.1578	0.1771	0.1776	0.0804	0.2332	0.1723
	K	-0.3275	0.0874	-0.1591	-0.328	0.1719	0.3901	0.2961	0.1706
15 - 30	Ex. acidity	-0.0588	0.1018	0.0331	-0.0586	0.0995	-0.1716	-0.0377	0.1032
	Ex. Al	-0.1226	0.1132	-0.0439	-0.1181	0.1049	-0.0783	-0.0067	0.1084
	Ca	0.1943	0.1053	0.0579	0.1814	-0.0612	0.2196	0.0886	-0.0612
	Mg	0.232	-0.0202	0.0112	0.2175	-0.0542	-0.1297	-7663	-0.0533
	Na	-0.1338	-0.0717	-0.022	-0.1127	0.0157	-0.1299	0.0042	0.0141
	K	0.1437	-0.1799	-0.1615	0.1213	0.2898	0.5352**	0.5310**	0.2896
30 – 45	Ex. acidity	-0.3307	-0.0971	0.0693	-0.2967	0.2034	0.4674**	0.3777*	0.2236
	Ex. Al	-0.0966	-0.1024	-0.0274	-0.098	0.1165	0.297	0.2492	0.1388
	Ca	-0.1756	0.0312	-0.0741	-0.2599	-0.1244	0.0116	0.0376	-0.1353
	Mg	-0.0354	-0.1752	0.1764	0.1038	-0.0432	-0.2404	-0.2089	-0.0612
	Na	-0.0922	-0.0213	0.1033	-0.0978	-0.813	-0.1555	-0.1184	-0.928
	K	0.0235	-0.0337	0.0118	0.0103	0.0173	-0.0688	-0.1025	0.0111
45 – 60	Ex. acidity	0.078	-0.043	-0.2113	0.0354	0.2431	0.0434	0.2535	0.2199
	Ex. Al	0.1264	0.2237	0.0944	0.0975	-0.1296	0.07	0.0786	-0.0031
	Ca	0.0432	0.1129	0.3474*	0.0855	0.1076	0.1246	0.1177	0.3337*
	Mg	-0.0702	-0.1078	-0.2278	-0.119	0.1384	0.1776	0.0328	0.0422
	Na	0.3564*	0.0216	0.3474*	0.3838*	0.2805	-0.2402	-0.0765	0.0041
	K	0.4133**	0.3271	0.3658*	0.4512**	0.2984	0.3404**	0.3336	0.246

RL - Root length TRW - Total root weight FRW - Fine root weight ROD - Rooting density

Ex. Al – Exchangeable Aluminium

* - Significant at 5 %, ** - Significant at 1 %

Significant and positive correlation coefficient between Ca at 10 cm lateral distance and root parameters viz., root length ($r = 0.3286^{*}$), fine root weight ($r = 0.3166^{*}$) and rooting density ($r = 0.3236^{*}$) was noticed in *C. rotang.* At a lateral distance of 30 cm, Ca showed significant and positive relation with root length ($r = 0.2828^{*}$) and rooting density ($r = 0.2749^{*}$) in the same species. But in *C. thwaitesii* the only relation observed was with total root weight ($r = 0.3200^{*}$) at 30 cm radial distance (Table 27).

Correlation coefficient between Ca and root parameters such as root length ($r = 0.3789^{*}$) and rooting density ($r = 0.4329^{**}$) in the surface layer of soil was significant in *C. rotang* while its positive and significant correlation with fine root weight ($r = 0.3474^{*}$) and rooting density ($r = 0.3337^{*}$) was observed at 45-60 cm depth in *C. rotang* and *C thwaitesii* respectively (Table 26).

Exchangeable Mg

Mean value of exchangeable Mg content in the soil varied from 0.009 to 0.018 per cent in *C. rotang* and in that of *C. thwaitesii* it varied from 0.009 to 0.020 per cent.

At 30 cm radial distance, Mg was significantly and positively correlated with total root weight ($r = 0.3292^{*}$) in *C. rotang* , but in *C. thwaitesii* it was significantly and negatively correlated with total root weight ($r = -0.2557^{*}$) (Table 26).

5.3.3.3. Regression analysis

Based on the above findings, an attempt was made to fit regression model. Two response functions relating fine root weight and rooting density to the soil properties were fitted using stepwise regression techniques in each of these species.

The models fitted through stepwise regression in *C. rotang* were

1) FRW = 0.0724 + 0.0769 OC – 0.02196 SM +1.4692 Ca (Adj. R^2 = 0.4326)

(0.0418) (0.0092) 0.0046) (0.4734)

2) $$\text{ROD} = -0.0732 + 0.1601\ \text{OC} + 0.0051\ \text{Sand} + 3.7036\ \text{Ca} - 0.0346\ \text{SM} \quad (\text{Adj.}R^2 = 0.4451)$$

$$(0.1279) \quad (0.0232) \quad (0.0017) \quad (1.1248) \quad (0.0117)$$

FRW – fine root weight, ROD – rooting density, OC – organic carbon, SM – soil moisture, Ca - calcium

In the 1st model, fine root weight of *C. rotang* was found to be influenced significantly by Organic carbon, Soil moisture and Calcium. From the adj. R^2 it was revealed that 43% of the variations in fine root weight of *C. rotang* could be explained by these soil variables. Among the soil properties, the most correlated variable with the fine root weight was organic carbon. It explained 31 % of the variations in fine root weight followed by soil moisture and calcium explaining 9% and 3% of the variations respectively.

In the 2nd model, rooting density of *C. rotang* was influenced significantly by Organic carbon, Sand, Calcium and Soil moisture. Adj. R^2 revealed that 45 % of the variations in rooting density of *C. rotang* could be explained by these soil variables of which the most correlated variable with the rooting density was organic carbon. It explained 30% of the above variations followed by sand explaining 7 % of the variation. Calcium and soil moisture explained 4% and 3% of the variations respectively in rooting density.

The models fitted through stepwise regression in *C. thwaitesii* were

1) $$\text{FRW} = -0.0612 + 0.0014\ \text{K} + 0.0037\ \text{Sand} - 0.0030\ \text{Gravel} \quad (\text{Adj. } R^2 = 0.4500)$$

$$(0.0679) \quad (0.0.0002) \quad (0.0011) \quad (0.0010)$$

2) $$\text{ROD} = 0.1816 + 0.0028\ \text{K} - 0.0085\ \text{Gravel} + 0.0856\ \text{OC} + 0.7488\ \text{Av N} \quad (\text{Adj. } R^2 = 0.6252)$$

$$(0.0890) \quad (0.0003) \quad (0.0016) \quad (0.0275) \quad (0.2760)$$

FRW – fine root weight, ROD – rooting density, OC – organic carbon, K- potassium,

Av. N – available nitrogen

In the 1st model, fine root weight of *C. thwaitesii* was found to be influenced significantly by available potassium, sand and gravel. From the adj. R^2 it was revealed that 45% of the variations in fine root weight of *C. thwaitesii* could be explained by these soil variables. Among the soil properties, the most correlated variable with the fine root weight was available K. It explained 35 % of the variations in fine root weight followed by sand and gravel explaining 7% and 3% of the variations respectively.

In the 2nd model, rooting density of *C. thwaitesii* was influenced significantly by Potassium, gravel, Organic carbon and available nitrogen. Adj. R^2 revealed that 63 % of the variations in rooting density of *C. thwaitesii* could be explained by these soil variables of which the most correlated variable with the rooting density was K. It explained 44% of the above variations followed by gravel explaining 13% of the variation. Organic carbon and available Nitrogen explained 4% and 2% of the variations respectively in rooting density.

Table 27. Mean values of soil parameters

SP	RD	DE	Physical properties						Soil reactions & nutrients				Exchange characteristics					
			SMO	BD	GRA	SAND	SILT	CLAY	pH	OC	Av. N	Extr. P	E. Ac	E. Al	Ca	Mg	Na	K
	(cm)	(cm)	%	g cm^{-3}	%	%	%	%	-	%	%	ppm	geq/100g	geq/100g	%	%	ppm	ppm
C. rotang	0 cm	0-15	6.032	1.241	26.890	44.200	19.600	36.200	5.220	1.378	0.054	0.978	0.280	0.192	0.041	0.013	55.500	107.900
		15-30	6.622	1.327	31.464	32.200	35.000	32.600	5.060	0.834	0.052	1.006	0.370	0.340	0.038	0.012	44.200	99.900
		30-45	7.920	1.505	35.076	35.200	29.000	35.800	4.994	0.626	0.044	0.626	0.250	0.260	0.044	0.009	60.500	92.500
		45-60	6.814	1.466	39.814	33.200	34.400	32.400	5.040	0.576	0.049	0.790	0.130	0.030	0.052	0.010	71.200	113.796
	10 cm	0-15	6.191	1.299	24.573	41.600	21.600	36.800	5.200	1.774	0.057	1.542	0.217	0.190	0.055	0.013	46.633	103.467
		15-30	7.359	1.376	31.983	37.400	21.600	41.000	5.113	1.123	0.053	0.854	0.293	0.280	0.047	0.018	47.300	85.000
		30-45	7.682	1.392	36.859	33.800	23.200	43.000	5.107	0.701	0.043	0.841	0.243	0.173	0.046	0.011	47.300	75.833
		45-60	7.383	1.491	34.889	29.800	34.000	36.200	5.127	0.519	0.040	0.896	0.130	0.090	0.048	0.013	46.533	77.000
	30 cm	0-15	6.810	1.383	29.843	42.400	32.000	25.600	5.067	1.631	0.069	1.423	0.303	0.283	0.050	0.015	45.733	90.333
		15-30	7.476	1.288	30.933	36.600	34.000	29.400	5.073	1.129	0.061	0.946	0.343	0.277	0.047	0.010	44.333	74.767
		30-45	7.235	1.432	36.859	31.200	33.000	37.800	5.133	0.767	0.047	0.783	0.197	1.820	0.048	0.013	44.167	74.767
		45-60	7.317	1.417	37.265	29.800	37.600	32.600	5.120	0.627	0.037	0.769	0.098	0.030	0.049	0.012	43.467	76.800
C. thwaitesii	0 cm	0-15	9.848	1.328	32.236	44.400	23.200	32.400	4.740	1.466	0.064	0.810	0.180	0.140	0.040	0.017	42.400	211.500
		15-30	10.412	1.323	40.176	39.600	20.000	40.400	4.600	1.150	0.065	0.960	0.210	0.140	0.048	0.013	42.500	124.400
		30-45	11.526	1.460	42.894	31.000	40.000	29.000	4.680	0.766	0.045	1.988	0.180	0.150	0.041	0.020	43.500	76.100
		45-60	12.052	1.552	42.516	33.600	31.200	35.200	4.700	0.614	0.045	1.016	0.080	0.080	0.052	0.017	46.100	69.000
	10 cm	0-15	10.304	1.393	36.491	43.000	26.400	30.600	4.620	1.927	0.106	1.142	0.207	0.153	0.048	0.012	41.367	153.300
		15-30	11.671	1.401	41.243	34.000	24.600	41.400	4.540	1.169	0.055	0.754	0.263	0.213	0.041	0.010	41.967	101.300
		30-45	11.721	1.438	45.761	35.000	29.000	36.000	4.627	0.881	0.053	0.537	0.177	0.137	0.046	0.010	45.800	79.300
		45-60	12.891	1.565	45.257	31.200	44.400	24.400	4.640	0.552	0.045	0.687	0.113	0.037	0.045	0.013	43.300	62.933
	30 cm	0-15	9.684	1.471	34.313	46.800	26.400	26.800	4.533	1.876	0.059	1.274	0.297	0.230	0.044	0.009	40.333	143.400
		15-30	11.483	1.432	43.079	39.600	29.000	31.400	4.567	1.184	0.052	0.733	0.303	0.257	0.038	0.011	40.133	89.667
		30-45	11.635	1.484	48.654	32.400	28.600	39.000	4.680	0.729	0.041	0.481	0.203	0.133	0.041	0.013	42.133	75.767
		45-60	11.101	1.552	46.391	29.000	44.600	26.400	4.733	0.607	0.044	0.866	0.110	0.053	0.044	0.013	43.133	64.667

SP- Species RD-Radial distance DE- Depth SMO- Soil moisture BD- Bulk density GRA- Gravel OC- Organic carbon
Av. N- Available nitrogen Extr. P – Extractable phosphorous E. Ac – Exchange acidity E. Al – Exchangeable aluminium
Ca – Calcium Mg – Magnesium Na – Sodium K - Potassium

Chapter 6.

DISCUSSION

6. DISCUSSION

Knowledge of the plant root systems is the key to fundamental ecological understanding in many fields of botany and their applied sciences. Still relatively less is known about roots than about above ground parts of plants. In field conditions, the root systems of plants are often much more variable in form than their shoots. This is due both to environmental and morphological characteristics. Within the rooting depth, soil physical and chemical factors can at any one time vary to an extent, which has no parallel in the above ground environment. Moreover the pattern of growth of roots is less determinate than that of shoots and the enhanced growth of a small favourably placed part of the root system may largely compensate for restricted growth elsewhere.

A thorough knowledge of the structure and development of root system is essential for full understanding of the ecological requirements of each plant species, which in turn, is a necessary basis for silvicultural decisions. Besides, species are distinguishable by their characteristic root morphology (Weaver, 1926). The growth of plants during the early phase of a plantation, when seedlings respond vigorously to silvicultural manipulations, is regarded as critical. During this period, the roots confined initially as a mat in a narrow planting wedge, ramify through out the soil.

Silvicultural practices to be adapted for rattans, when raised as a plantation, are unknown. A basic knowledge of its root morphology, volume of soil exploited and the influence of edaphic factors on the root system is necessary for standardization of nursery practices. Hence, these aspects with respect to the two species of rattans are discussed which will prove to be of help in standardizing the nursery practices of rattans.

6.1 ROOT MORPHOLOGY AND GROWTH PATTERN

Woody monocots in general, posses profusely branched fibrous root system. Experimental data available on the morphology and growth pattern of roots are however mostly confined to dicots.

6.1.1 Growth characteristics

The type of seed germination and the nature of origin of roots were similar for the two species studied. The primary root in rattans is formed in embryogeny, as in other monocots; but it is short lived. (Bavappa and Murthy,1961; Tan, 1983). In many palms, the embryonic root, with plumule is pushed out of the seed by a haustorium but in rattans the germination is adjacent ligular as is reported in certain other palms (Tomlinson,1961).

The growth of primary root is soon arrested and is replaced by adventitious roots produced from the obconical base. These roots produce laterals and sub laterals as they grow. Same type of development is reported in oil palm, *Elaeis guineensis* (Tinker, 1976) and in *Areca catechu* (Bavappa and Murthy, 1961).

The radicle of rattans, and of monocotyledons in general, has a limited life span, since it is a low diameter axis, with exclusively primary growth. As the absorbing zones are extended through branching, the place of attachment of the radicle to the above ground part becomes a veritable 'bottle neck" and the radicle alone is unable to meet increasing demand from the above ground organs. The plant then produces numerous adventitious roots, which thus by-pass the bottleneck region. Adventitious roots are found to develop from the base of the stem and also from small rhizomes.

The seedlings axis is massive and obconical, reflecting its primary development by addition of successively wider internodes. In this phase the type of growth has been referred to as establishment growth (Tomlinson, 1970). The base of the stem developed in the juvenile phase is commonly bulbous and wider than the distal part, which must offer mechanical advantages as well as large surface for root development. A large number of adventitious or secondary roots arise from this base, as the seedlings grow. Vertical and horizontal roots were observed in both the species but no pneumatophores were present.

Davis (1961) described the roots of arecanut in relation to their origin, size, shape, function and structure and reported the presence of pneumatophores or breathing roots. Lakshmana (1993) also reports the presence of negatively geotropic roots or pneumatophores in the mature plants of *C. nagbettai*, C. metzianus and *C. rotang*. Dransfield (1974) studied the root system of *C. caesius* and observed four distinguishable roots in swamp soil; horizontal spreading roots, vertical geotropic roots, vertical apogeotropic roots and fine lateral roots. The tendency to produce pneumatophores in rattans is generally seen when the plants are growing in areas where soil is flooded frequently or in marshy areas. In the present study the experiment was conducted in a dry zone and hence there was no necessity for development of breathing roots.

The number, length and diameter of main roots as well as laterals increase with age. A comparative study of the number of roots between species of rattans show that there is significant difference only in the initial stage. As they grow older, all species behave in the same manner. When compared to other palms, the number of roots in *Calamus* is very less , but the roots are very stout and strong as reported also by Mahabale, (1982).

A 12 month old plant of *C. viminalis* developed 23 main roots (Banik and Ahmed, 1986) while a 12 month old *C. rotang* and *C. thwaitesii* developed about 5 roots.

The number of main roots and their laterals increase with age in both the species. A significant difference between *C. rotang* and *C. thwaitesii* with respect to the number of main roots, laterals and sublaterals is seen only at 26th month. In all other instances it is non significant (Table 1).

C. vimimalis developed about 39 main roots with an average length of 94.5 cm and average diameter of 0.41 cm within 36 months (Banik and Ahmed, 1986). At the end of 3 year period, both the species had almost the same number of main roots (Table 1). The laterals were more in *C. thwaitesii* while sublaterals were more in *C. rotang*.

In this study the length and diameter of main roots increase gradually with age. A significant difference between the two species is noticed with respect to length and diameter of laterals at the end of 38th month Table (2 & 3). Similarly significant difference exists with respect to the diameter of main roots at the end of 14 months.

In *Calamus viminalis*, the primary root attains a length of 18.5 cm in the first month. While in C. *rotang* and *C. thwaitesii*, it has an average length of 10.68 cm and 14.39 cm respectively at the end of 2 months.

The roots in rattans radiate to all sides from the rooting base. Most of the roots reside very close to the palm. In a 3 year old *C. thwaitesii* the average horizontal spread was 61.60 cm and in *C. rotang* 91.80 cm. ie, about 30 cm and 45 cm radius around the stem. Similar results were reported from *Areca* also (Bavappa and Murthy 1961; Mohapatra *et al.,* 1971) Here most of the roots were within 30-60 cm radius in younger stages and in a five year old areca palm,96 % of its roots spread in a zone of 50 cm radius around the palm. The age factor influences the root distribution pattern and hence determines the area around the plants where soil work needs to be done and for opening basins to hold water and for manuring. For a 3 year old *C. rotang* soil work should be done at a radius of about 45-50 cm (91.8 cm horizontal spread). For a 3 year old *C. thwaitesii* the radial distance for soil work is to be about 30 cm.

A comparison of vertical spread of the roots between *C. rotang and C. thwaitesii* was statistically non significant. In *C. viminalis* also the difference of depth between the roots and the soil surface from root base to tip was statistically non significant. Here the root moved almost parallel to the soil surface. Presence of maximum number of ramified vertical rootlets within the first 30 cm from the base of the plant may be an adaptation to keep the stem erect (Banik and Ahmed,1986) . But in the rattan spp. studied roots are not growing parallel to the soil surface. They grow vertically downward up to a distance of 29.84 cm in *C. rotang* and 39.05 cm in *C. thwaitesii.*

6.1.2. Soil exploitation

Volume of soil available for rooting is an important factor governing the growth of seedlings. In fact, the soil is only partly utilised and a large proportion of the soil is not being exploited by the roots.

In *C. rotang*, soil volume exploited in the second year is about 30 times the volume exploited in the first year. There is 219 times increase in the exploited soil volume in the third year. In *C. thwaitesii* in the first two years the soil volume exploited is more or less the same while 61 times increase is seen in the third year (Table 8). A comparison between species shows that *C. rotang* is exploiting more soil volume than *C. thwaitesii.*

6.1.3. Effective soil volume

In the nursery, the plant seldom has enough soil at its disposal to allow optimal development of its root system. However, often a considerable restriction of soil volume hardly impairs growth of the plant and only a small part of the amount of nutrients present is absorbed by a crop.

Stevenson (1967) defined the effective soil volume as the volume of soil that is able to supply water to a root system and that does not restrict the growth of those roots. By calculation, effective soil volume or Ve is a maximal 78.5 % (90.5 % with triangular spacing of roots) of a total volume that does not restrict growth. Below this point root density will decline sharply as soil volume increases, but between 78 and 100 % root density increase gradually, attended by restricted water supply and growth. For maximum effects from nutritional or water content treatments, plants should be provided with sufficient soil at least to approach the conditions laid down in the definition of effective soil volume. The smaller the plant, the easier it is to meet this provision.

In this study it is seen that the ratio $\frac{R_{\max}}{S}$ (root density) declines year by year. This shows that the effective soil volume has been attained in the two species. Silvicultural practices in the nursery can be regulated based on this observation. In the first year, while 446.78 cm^3 of soil is needed for *C. rotang*, 631.59 cm^3 of soil is needed for *C. thwaitesii* in the poly bag or other containers to attain the maximum growth of roots. In the second year, the effective soil volume is found to increase in *C. rotang* compared to *C. thwaitesii*. In the 3rd year, while the effective soil volume shows an enormous increase in *C. rotang*, it remains the same as that of the 2nd year in *C. thwaitesii* (Table 9).

Rattan seedlings can be outplanted from the polybag after one year of hardening in the nursery. For an optimal development of the root system, the bag should contain the effective soil volume.ie for *C.rotang* 446.78 cm^3 and for *C.rotang,* 631.59cm^3 . For *C.rotang* the bag size should be 14x10 cm of which 14 cm is the height of the bag and 10cm is the width. For *C.thwaitesii,* it should be 16 x 11.15 cm. If the seedlings need to be kept for the second year also, the bag size should be 27 x 21 cm for *C.rotang* and 18 x 15.5 cm for *C.thwaitesii.*

6.1.4. Rooting density

Efficiency in nutrient uptake is influenced by the rooting density. Rooting density can be expressed relative to either soil surface area (L_A =cm cm^{-2}) or soil volume (L_V =cm cm^{-3}). Newman (1969) reviewed data for a wide range of species and found that in Gramineae, reported values were in the range of 100 – 4000 and in herbs 52-310 that is considerably higher than in fruit trees. Atkinson & Wilson (1979, 1980) describes the consequences of a low L_A value. When a plant transpires, it withdraws water from the soil. This will come initially from soil immediately adjacent to the root with this zone being replenished from bulk soil. If the rate of withdrawal exceeds the rate of water movement through the soil to the root, that is the rate of uptake exceeds soil hydraulic conductivity, then the soil adjacent to the root will become drier than the bulk of soil and the rate of water flow into the root will decrease and may result in water stress. Localized drying occurs and thus the gradients of water potential at the root surface will reduce the uptake of minerals thought to be moved by mass flow. If root density is high, flow rates will always tend to be low and gradients at the root surface will be rare. Where root density is low, as in fruit trees, the contrary will be true.

Root density varies with depth. So reduced soil water potentials will not be the same at all depths and this will, therefore affect the balance of nutrient uptake from different parts of the soil profile.

In the present study, while *C. rotang* possesses a higher rooting density during the 1st year of growth, *C. thwaitesii* is with greater rooting density in the 2nd and 3rd year. The rooting density in both the species is found to be inversely related to the amount of soil exploited by the root system. Major contribution of the laterals and sublaterals towards rooting density of the plant occurs during the second year in both species of *Calamus* (Table 10).

Studies conducted by core metod at different depths and radial distances in the 3rd year reveals that rooting density is greater in *C. thwaitesii* compared to that of *C. rotang*. With respect to depth, rooting density is seen to be much higher in the upper 30 cm of soil compared to the lower 30 cm in both the species. While 81 % of the total rooting density is the contribution of the upper 30 cm of soil in *C. rotang*, 89 % of the total rooting density is contributed by upper 30 cm of soil in *C. thwaitesii*. At all depths other than 30 – 45 cm, rooting density is found to be more in *C. thwaitesii* compared to *C. rotang* (Table 18).

As far as the different lateral distances from the base of the plant are concerned, the percentage contribution of the rooting density within a soil depth of 0 – 60 cm at the centre of the rooting zone and at 10 cm away from the base of the plant is 36 % and 37 % respectively in *C. rotang*. While *C. rotang* shows almost the same rooting density at these regions, *C. thwaitesii* shows markedly more percentage root density (46 %) at the centre of the rooting zone than at 10 cm away from the plant (29 %) (calculated from Table 17).Since higher rooting density is observed in *C. thwaitesii*, this species will be more efficient in nutrient uptake.

6.1.5. Root intensity

The absorption of water and mineral nutrients by plants is often assumed to occur exclusively through the younger parts of the root system. However, in cereals, it is shown that to a greater or lesser extent, most of the root system is able to function as an absorbing surface, although the rate of absorption is greater in apical areas. (Graham *et al.*, 1974; Ferguson and Clarkson, 1975). Atkinson and Wilson (1979) found that woody roots also could function in absorption. Wilson and Atkinson (1979) found that the uptake of ^{45}Ca was higher in woody roots of F12/1 cherry and proved that in tree crops, all roots both woody and the newly formed, are apparently effective to some extent. When total root intensity is considered, *C. thwaitesii* is more efficient in absorption compared to *C. rotang* (Table 11), the percentage of total intensity being more at the surface layer (0-15 cm depth).

According to Wright (1951) the absorbing roots of oil palm are concentrated in the upper 10 cm of soil where as Grey (1969) observed predominance of the absorbing roots in the upper 30 cm soil.

In the rattan species studied, absorbing roots are found to be more in the upper 15 cm soil. In *C. rotang*, 83 % of the total root intensity is contributed by fine roots while in *C. thwaitesii*, 87 % of the total root intensity is the contribution of fine roots (Table 11). Thus *C. thwaitesii* is more efficient in absorption even when only the fine absorbing root are taken into account.

In *C. rotang*, absorbing roots are found comparatively more at a lateral distance of 10 cm followed by 30 cm away from the plant than that at the centre of the rooting zone. Unlike *C. rotang*, in *C. thwaitesii*, fine roots are maximum at the centre of the rooting zone than that at 10 cm and 30 cm away from the plant (Table 12).

Root activity decreased with increasing soil depth. In *C. rotang* about 76 % of the active roots are located at 0-30 cm depth while 86 % of the active roots in *C. thwaitesii* are located at 0-30 cm depth. About 70 to 80 % of the active roots are located at 0-20 cm depth for oil palm (Wright, 1951).

6.1.6. Root surface area

Root surface area measures the total absorptive area of the root and is especially important in the supply of an immobile nutrient to the plant.

In the two species of *Calamus* studied, main roots alone are present in the initial stage and are involved in absorption of nutrients. *C. thwaitesii* has more root surface area at this stage. With the initiation of laterals in the 1st year also total surface area/plant is more in

C. thwaitesii. However in the second year, *C. rotang* has more surface area due to the occurrence of more roots, both <2 mm and >= 2 mm. At the end of third year, the trend was reversed - *C. thwaitesii* thus having more root surface area compared to *C. rotang* (Table 13). However surface area of the fine roots, even though few in number were found to be greater in *C. rotang* due to their increased length and diameter. This is supported by the statement that plants with greater "specific root surface area" are more efficient and opportunistic absorbers of ions and water (Barber and Silver Bush, 1984). Such plants with root systems having greater specific root surface areas also appear to be more competitive in single and mixed plant communities (Eissenstat and Caldwell, 1988). Root system of *C. thwaitesii* is seen to be more efficient since it has got more specific root surface area.

6.1.7. Soil binding capacity

Binding effect on the soil particles and the promotion of soil aggregation are of direct value in soil conservation. The length and thickness of roots play an important role in binding the soil particles together. Fine roots with their close and elaborate network have greater binding capacity on the soil than thicker roots.

In the species studied, soil binding capacity shows an increase with age in *C. rotang* while in *C. thwaitesii* soil binding factor is found to be more in the 2nd year. The value of soil binding capacity after one year of growth in the rattan species varies from 149.6 – 174.7. Two year old rattan species have binding factor varying form 302.7 – 401.4 (Table 14). The soil binding capacity of grass roots were studied by Bhaskaran and Chakrabarty (1965). In the protected condition, the binding capacity varied from 219 to 876 in four species of grasses. Mathur *et al.* (1982) have noted that in *Populus ciliata,* a promising species for soil conservation, the soil binding factor after one year growth was 61.29 and after two years was 106.65. Dhyani *et al.* (1990) have calculated soil binding capacity factor for five species among which three were suggested to be more suitable in conservation forestry. Out of these, three, *Ougeinea* had maximum value (228) of soil binding capacity followed by *Leucaena* (152) and *Grewia* (131).

However, when compared to these species rattans are good soil binders. Comparison with grasses shows that the two species of rattans have a soil binding capacity more than certain species of grasses. In grasses, the binding factor in the second year is found to be varying form 219 to 876 while in the two species of *Calamus*, it varies from 302.7 to 401.4. Hence *C. rotang* and *C. thwaitesii* are good soil binders and have every possibility of being successful in soil conservation. Banik and Ahmed (1986) also points out that *C. viminalis* is likely to check soil erosion by its well developed horizontal spreading root system which anchors bulk of soil.

6.1.8. Shoot-root relationship

The common parameter for evaluating the relation between above and below ground growth of plants is the shoot-root ratio. It is a measure of the distribution of dry weight between shoot and root system of the plants. While Boonstra (1931, 1955) used shoot-root coefficient to explain the shoot-root relationship, Bray (1963) uses the inverse coefficient.

Many of the results of research works indicate that the common assumption of a persistent tendency towards a positive correlation between shoots and roots is not generally valid. However in the species of *Calamus* studied, there is a significant positive correlation between dry weights of shoot and root in each year. The shoot/root ratio of grass in the vegetative phase is constant under constant condition (Ennik and Hoffman 1983). In the present study, shoot-root ratio at the 2 month stage and after 1 year growth is found to be more in *C. thwaitesii* when compared to that of *C. rotang*. But at the end of 2 year and 3 year *C. rotang* has a high shoot- root ratio than *C. thwaitesii* (Table 16). Studies on the shoot-root relationship reveal that even though the shoot remains in the rosette stage in the two species of *Calamus*, the biomass increases simultaneously with an increase in root biomass. The growth is taking place for widening of the shoot base rather than lengthwise. Once the basal diameter specific for the stem is attained, the growth in length starts.

6.2. RHIZOME DEVELOPMENT

The genus *Calamus* is a clustering palm, with species ranging from closely clustering to open colonies produced by stolons (Dransfield,1978). The clustering was relatively close in both the species. The rhizome production in clustering palms begin only after building up the base of the primary shoot of potential maximum diameter which varies with species. In this study, *C. rotang* started rhizome production first since this is a small diameter one. *Calamus* exhibits a sympodial habit which is characteristic of monocotyledons. Rhizome development started in the two species along with the development of multiple stems. Each new shoot is developed from the axillary bud located near the base of the stem. Repetition of this process result in a clustered habit of the species. The lateral suckers develop from the axillary bud. These lateral suckers develop their own root system and become less dependent on the parent axis. *C. rotang* and *C. thwaitesii* differ in the time of elongation of the primary stem. While primary shoot elongates before the production of suckers in *C. rotang*, 3-4 suckers are produced before primary shoot elongation in *C. thwaitesii*.

Although rhizomatous habit is developed in *Calamus*, it differs form other palm like *Rhapis, Serenoa* etc., where the rhizome is of a creeping type.

6.3. ROOT GROWTH IN RELATION TO SOIL PROPERTIES

This part of the study is conducted to find out the relation, if any, between the root parameters and the soil properties. The extent of influence of soil properties on the root growth of the two species is discussed and the best suited species is determined.

In the present study, the different root parameters considered are root length, total root weight , fine root weight and rooting density. Root length, seems to be a good parameter for studying the process of nutrient uptake by plant roots (Nye and Tinker, 1969). Root weight, the most commonly used parameter for studies of root growth response to environment, is a good parameter for characterizing the total mass of roots in a soil. Root weight can be regarded as fundamental measure of photosynthate in a plant. The known shoot-root relations are based mainly on shoot and root weight. Rooting density which is the root length per unit soil volume is one of the best parameters for calculation of water uptake by plant roots (Grosskopf, 1950; Gardner, 1964; Taylor and Klepper, 1973, 1975).

6.3.1 Influence of radial distance on root growth

Morphology of root system is directed by genetic codes and attenuated by historical and contemporary environmental conditions. Root systems are seldom distributed uniformly within any given soil horizon of the root zone and the distribution pattern often account for plant competitiveness and tolerance to stresses. Radial distance, in general, has an inverse relationship with the root parameters since the roots are mostly concentrated immediately below the plant. This is very well seen in roots of *Calamus* also. Thus the plant root architecture itself is found responsible for this to a certain extent.

Data on root parameters studied at different radial distances show a gradual decrease in root growth with increase in radial distance in the two species of *Calamus*. The decrease in root length, total root weight, fine root weight and rooting density is not significant in *C. rotang.* However these root parameters are found significantly higher at the centre of the rooting zone in *C. thwaitesii.* Similar results are reported in *Pinus sylvestris, Pinus radiata, Pseudotsuga menziesiil* and is supported by the work of Roberts (1976), Eis (1974) and Angelov (1976).

In *Calamus* fine roots are observed more at the immediate base of the plant which may be one of the reasons for the radial decrease in root parameters. This is supported by the work of Roberts (1976). He attributes this tendency of radial decrease in root parameters to the changes in fine root fraction in *Pinus sylvestris*.

Concentration of larger roots and the initiation of fine roots on them, around the root stock in *Calamus* species also probably account for the significant increase in the root parameter at this region. Studies by Eis (1974) and Angelov (1976) can be cited in support of this. Eis (1974) concludes that the greatest density in the Douglas–fir (*Pseudotsuga menziesiil*) is usually around the root stock because of the greater concentration of large roots, on which fine roots originated. Despite the wide potential and actual range of root spread, the highest concentration of roots seem to occur in a much smaller zone, as small as 0.3 to 1.0 m^2 close to the trunk in apple trees (Angelov, 1976). Nambiar (1983) notes that in radiata pine plantations, there is small decrease in concentration of roots radially form the stems of very young trees.

Reynolds (1970) finds no apparent rooting preference correlated with compass direction in *Pseudotsuga taxifolia*. However, he agrees that there is an inverse correlation between root length and distance from the nearest tree trunks, though not sufficient to account for any more than a fraction of the variability.

6.3.2. Influence of soil depth on root growth

The distribution of plant roots with depth, under field conditions, exposes different parts of the root system to different nutritional conditions.

Studies based on the data with respect to the root parameters in *Calamus* at different depths reveal that in most of the cases there is a significant decrease in root growth with increase in the soil depth. Higher root growth is observed in the surface layer of soil (0-15 cm) in both the species. The results also show the large contribution made by the upper soil horizons to the total root quantity. The declining root density with depth is a real reflection of the field situation. Such instances have been reported by Roberts (1976) in a *Pinus sylvestris* plantation. According to Ford and Deans (1977) spatial variation in the vertical plane seems more consistent. With a few exceptions, most roots in apple trees are found at 0 to 80 cm and approximately 70% root weight occurs at 0 to 30 cm depth. In *Prunus* species, as in other fruit types, the majority of roots were found in a more restricted zone (0 to 60 cm depth) with significant numbers found at 0 to 25 cm (Atkinson, 1980).

The increased occurrence of thicker roots at the basal region of *Calamus* plants appears to have a strong influence on the total weight of roots in them. This is being supported by the studies of Nambiar (1983) in radiata pine plantations in which he attributes increased weight of roots to their increase in thickness.

Fine roots in both species of *Calamus* are predominantly in the surface soil, (46 % in *C. rotang* and 57 % in *C. thwaitesii*) at 0-15 cm. This result is in accordance with that of Eis (1974) and Raper and Barber (1970). Eis based on his investigation concludes that the greatest concentration of fine roots is in the top 10 cm of mineral soil in Western Hemlock, Western Red cedar and Douglas fir. Raper and Barber (1970) have noticed that the majority of Soyabean root weight is contained within the upper 15 cm of soil when grown in undisturbed field soils.

6.3.3 Influence of soil properties on root growth

Root systems and root morphological components (tap root, basal roots, adventitious roots, and lateral roots) although genetically controlled, are highly variable in growth and development even in optimum environments as compared with their associated shoot characteristics. Therefore fluctuating soil environments (soil pH, moisture, temperature and nutrients) may have major impacts on root growth, subsequent seedlings shoot growth, and ultimately yield. An understanding on these aspects can assist in developing and utilizing cultural and/or management practices for optimum seedling growth and crop yields.

6.3.3.1 Influence of soil physical properties

Root development in the soil is influenced by soil physical properties (bulk density, porosity, aeration, water content, temperature and mechanical strength and impedance) as well as the nature of horizons in the soil profile. Soils vary widely in their physical properties and hence in their ability to support root growth. Besides these, soil morphology and crop management practices can also influence root growth by altering soil physical and morphological properties (Singh and Sainju, 1998).

The correlation studies between the root parameters and the soil physical properties reveal the positive ad negative influence of the different physical factors on the root growth of *Calamus* at different radial distances as well as depths. However the results reveal that depth of soil has no definite influence on root growth of *Calamus*. In this context, it should be recalled that any species will have its own root architecture which is genetically controlled. If there is no much hindrance in the soil, the same architecture will be expressed by the plant. In the present study, there was no hindrance in the soil and hence the plant could express its root architecture. The results thus show that more root growth occurs closer to the base of the plant at a depth of 0-15 cm. In the given soil, each property of soil has its own trend already. Thus, both inherent root architecture and variation of soil properties at different depths have an over all effect on the rooting pattern.

The results obtained when the correlation studies were carried out between root parameters and soil properties irrespective of radial distances and soil depths are worth mentioning and these are highlighted in the following paragraphs.

Soil moisture shows a highly significant negative correlation with the different root parameters in both species of *Calamus*. Hence a higher root growth occurs in *Calamus* at regions where soil moisture is comparatively less. This could be well explained since root growth in both these species is found to be more at the surface layer where moisture is comparatively less. Eventhough both the species were grown in the same area with uniform climate and soil conditions, soil moisture values with respect to *C. thwaitesii* were found to be significantly higher than *C. rotang*. This indicates that water consumption is comparatively less in *C. thwaitesii* and hence would be a suitable species in areas of water scarcity.

In this study, *C. rotang* has lesser root length compared to that of *C. thwaitesii*. Soil moisture stress can be suggested as a reason for this. *C. thwaitesii*, which does not require much moisture overcomes this without having an inverse effect on the root length. This is in fact supported by the work of Korikanthmath (1998). They have noted that soil moisture stress imposed on cardamom seedlings resulted in reduced root length.

Studies in *Calamus* reveal high negative correlation for gravel with the root parameters in both the species. Presence of gravel in the soil usually cause hindrance to the growth of roots. The results of the present study also support the above statement.

Sand shows highly significant positive correlation with all the root parameters studied in both the species of *Calamus*. It increases porosity of the soil thereby enhancing root growth as is seen in the present study. In this study silt also shows negative correlation with the different root parameters in both species. However it is highly negatively significant at 10 cm away from the plant in *C. rotang* where the root intensity is found more. In *C. thwaitesii,* silt shows high negative correlation with root parameters, closer to the plant and at 10 cm away from the plant where its root intensity is more. Lower porosity is suggested as one of the reasons for inhibition of root growth (Petcu *et al.,* 1997) and is applicable in the case of silt.

Bulk density, in this study is not correlating with any of the root parameters in *C. rotang*. This might be due to the fact that the seedlings of *Calamus* have not grown to produce roots to such an extent as to find any correlation with the bulk density of the soil. However, bulk density is found to show an increase with soil depth as well as lateral distance from the plant. Studies by Petcu *et al.* (1997), Nunez *et al.* (1999), Lav-Bhushan *et al.* (1999), Goodman and Ennos (1999) and Imhoff *et al.* (2000) support the above statement.

Petcu *et al.* (1997) have shown that increased bulk density inhibits root growth. Nunez *et al.* (1999) on comparing root growth of maize cv. HIMECA 2000 on loamy soil columns with bulk densities of 1.35 mg/m^3 through out the column, and partly with bulk densities of 1.35 mg/m^3 and partly with 1.55 mg/m^3, observed a reduction in root biomass production, length and density in the second case. Lav- Bhushan *et al.* (1999) studied the effects of depth, bulk density and aeration status of root zone on root growth and yield of wheat and have noticed that in a soil of clay loam texture, root mass decreased with the increase in root zone depth provided the root zone was aerated. Goodman and Ennos (1999) have shown that penetration resistance was higher in soils with high bulk density than those with low bulk density. They have also noted that in strong soil the roots of both sunflower and maize were thicker near the stem base compared to those in weaker soil.

According to Imhoff *et al.* (2000) in *Pennisetum purpureum* (elephant grass) significant differences were observed in soil physical properties, with higher values of bulk density and soil resistance to penetration between the plants than beneath the plants.

6.3.3.2 Influence of soil chemical properties on root growth

The soil (edaphic) factor deserves much attention in any root studies not only because of the intimate surface contact between plant and soil which leads to a strong mutual influence but also because of the tremendous complexity and dynamic nature of soil. Uptake by the roots is influenced both by the root system and by its environment which in addition to directly affecting uptake, will indirectly influence through effects on root growth also. The total volume of the root system, root density, the periodicity of both growth and activity in relation to tree demand , and the distribution of the root system through a soil volume where all horizons are not equally able to supply nutrients, will all be important (Atkinson and Wilson, 1980).

Plants generally absorb only small proportions of some of the nutrients in soil, eventhough they may be in a suitable chemical form. The value of nutrients depend on their accessibility to roots which, in turn is related to their mobility in soil. The importance of soil root contact has been discussed by Atkinson and Wilson (1979) who suggested that, it is likely to be better with woody, than with white roots.

All horizons in the soil volume are not equally able to supply nutrients to the plant. The concentration of most elements are highest at the soil surface and decrease with depth, although the rate of decrease differs between elements. In addition, other soil factors, eg. temperature, varies with increasing depth and may differentially affect the uptake of different nutrients (Tromp, 1977). The effect of root distribution on nutrient uptake, however will depend upon the concentration of nutrients and the length of root at different depths and the extent to which roots in any given part of the profile are absorbing at a rate close to maximum. The extent of relationship between the root growth in *Calamus* and the soil chemical properties is being highlighted in the following paragraphs.

Correlation studies were carried out between root parameters and the soil properties at different depths, radial distances and also irrespective of these depths and radial distances.

All the three nutrients in the soil – organic carbon, available N and extractable P are found to show significant positive correlation with almost all the root parameters in *C. rotang*. With regard to organic carbon, a higher percentage is noted in the surface soil (0-15 cm depth) at all the radial distances and shows a gradual depthwise decrease in both the species of *Calamus*. O. C is found to be highly significant and positively correlating with the root growth measurements in both the species studied. Studies by Gill *et al.* (1999) in the short grass steppe of Eastern Colorado support this. They have noticed a higher proportion of total root biomass in the surface soils and this layer was with maximum amount of organic carbon.

In this study, available nitrogen is found to be positively correlating with different root parameters in both the species of *Calamus.* Concentration of N in the deeper layers (30 – 60 cm) of soil when compared to the upper layers (0 – 30 cm) is found to be less with respect to both the species of *Calamus*. This difference in the soil N concentration between the upper and deeper layers of soil is seen to be much correlated to variation in the vertical distribution of roots, since the root parameters also decrease with soil depth. Similar results have been reported by Cavelier (1992) based on his studies on fine root biomass and soil properties in two types of forests. He had found an exponential reduction of root biomass with increasing depth, and most of the variation in the vertical distribution of roots <2 mm in diameter was explained by the concentration of nitrogen in the soils. The root intensity in both the species of *Calamus* is found to be much higher at 0 – 30 cm soil depth where N also is in higher quantity. This is in fact supported by the work of Andrews and Newman (1970) who found that N uptake depended upon the relative amount of roots in the soil. In *Calamus,* available N at the surface layer of soil is present at its higher concentration at a certain distance away from the centre of the rooting zone. Probably, the slow mobility of N ions in the soil, towards the rooting zone could account for this. Wiersum (1962) also suggests that the proportion of the total supply of nutrients that is used depends on the mobility of nutrient ions.

Vigorous branching seen in both the species of *Calamus* at 0 – 30 cm depth also correlates well with increased nitrogen present there. This is supported by the fact that a rich supply of nutrients, especially N promotes vigorous branching in roots.

Phosphate ions diffuse so slowly that their rate of arrival at the soil/root interface rather than subsequent physiological processes may largely govern absorption. It appears that when the movement of ions towards roots is limited by diffusion, the amount absorbed by a root system will vary with its surface area and total length (Russell, 1977). It is well known that pH at the root surface may differ from that in the bulk soil, the situation being highly variable depending on the ionic balance. Riley and Barber (1971) have suggested that these pH changes may influence the uptake of phosphate. In addition, it seems possible that the accumulation of ions over the root surface (eg. Ca or SO_4) may affect the mobility of other ions (Hoffman and Barber, 1971) . For P, because of its low mobility in soil, contact is always likely to be important.

Extractable P is significantly and positively correlating with root length, fine root weight and rooting density in *C. rotang*. In *C. thwaitesii* also significant positive correlation exists with fine root weight.

Content of P in soil is more with respect to *C. rotang* than *C. thwaitesii,* which means that the consumption of P is lesser in *C. rotang*. The formation of cluster roots in plants is an indication of low P (Neumann *et al.*, 2000) Frequent occurrence of cluster roots in *C. rotang* is observed in this study and hence can be regarded as a morphological expression of lesser consumption of P by the species.

C. thwaitesii attains more root surface area per plant than *C. rotang* at the end of 3rd year. Increased utilization of soil P may have resulted in this. And this means that increase in the soil P is directly related to the root surface area. This is supported by work of Hallmark and Barber (1984) who concluded that increasing soil P increased root surface area per plant and root surface area per gram of root.

When compared to *C. rotang*, *C. thwaitesii* is with more root length at the end of 3 years. This may be due to an increased uptake of P and has ample evidence form the work of Newman and Andrews (1973). According to them root length is likely to be functionally related to nutrient uptake from soil. Studies by Khasawach and Copeland (1973) in cotton (*Gossypium hirsutum*) is also an added evidence for this. They have found that P increased the root length in the species. Contrary to this, Taylor and Goubran (1976) concluded that it was the P stress that led to an increase in root length and suggested that the plant adapted to the stress by developing an exploiting type of root system.

With respect to soil reaction (pH), the soil surrounding *C. thwaitesii* is more acidic, even though both the species are grown in similar areas and subjected to uniform conditions. On laboratory examination it is found that root exudates of *C. rotang* contained more Ca than of *C. thwaitesii,* and it could be the mechanism of plant to thrive under less pH conditions.

Calcium status of a soil is fairly well correlated with its pH, both being biologically very active and have different effects upon plants. In this study, mean content of Ca in the soil around both *C. rotang* and *C. thwaitesii,* is more or less the same. Significant positive correlation is found for Ca with root growth in *C. rotang* while no such correlation has been obtained in *C. thwaitesii.* This gives an indication that presence of Ca in the root exudates of *C. rotang,* may be a probable reason for its positive correlation with root growth. The displacement of Ca ions by Al from the root apoplast exchange sites may be suggested as a reason for not obtaining any correlation for Ca with root growth in *C. thwaitesii.* Joslin *et al.* (1988) and Cronan *et al.* (1989) noticed an inverse relationship between concentrations of soluble Al in the rhizosphere and foliar tissue concentrations of Ca and Mg. One of the major hypotheses for this observation is that Al displaces Ca and Mg from the root apoplast exchange site (Wagatsuma, 1983) thereby inhibiting the active uptake of these essential nutrients (Godbold *et al.*, 1988).

The two soil properties, exchange acidity and exchangeable Al do not have any influence on root growth in *C. rotang.* The reason for this could be attributed to the nullifying effect on exchange acidity and exchangeable Al by the cation containing exudates of *C. rotang.*The positive correlation between these soil properties and root growth in *C. thwaitesii* suggest that this species favours more acidic soil.

Another important factor noted in this study is the highly significant positive correlation between K and root growth in *C. thwaitesii.* But no such correlation existed in *C. rotang.* It is a fact that monocots usually prefer K and this is clearly evident in *C. thwaitesii.* Unlike in *C. thwaitesii*, presence of Ca containing root exudates in *C. rotang* lead to a change in the pH of the soil around the species. This change in the soil pH is probably responsible for the root affinity towards divalent cations such as Ca rather than monovalent cations such as K. This is also supported by the studies in red spruce (*Picea rubens*), which grows in acidic forest soils (Cronan, 1991). In this study, root affinity for the divalent cations was much sensitive to pH changes.

6.3.3.3 Regression analysis

Step wise multiple regression analysis carried out in *C. rotang* reveals that variations existing in the fine root weight is due to organic carbon, soil moisture and exchangeable Ca content of the soil. The rooting density of this species is being influenced significantly by the above soil properties together with sand. In C. *thwaitesii*, variations in fine root weight is being explained by the soil properties viz., gravel, K and sand and the variation in rooting density of this species is explained by available N, gravel, K and O C.

In short, the root growth of *Calamus* during the early stages is generally influenced by the soil properties such as soil moisture, sand, Organic carbon, available N, potassium and Calcium.

This study on root morphology and development in *C. rotang* and *C. thwaitesii* reveals that *C. thwaitesii* having more rooting density, total root intensity, absorbing root intensity and root surface area per plant, can be considered as the more efficient and suitable species for any area similar to Palappilly. This species seems to be more favourable for areas with water scarcity since water consumption is lesser in it. From the effective soil volume calculated in each species size of the polybags required for raising the seedlings in the nursery is found out. The horizontal spread of the root system and the percentage of total and absorbing root intensity in each of the species help in regulating the silvicultural practices accordingly. The radial distance at which the soil work and manuring is to be done for each species has been stated in the study. The soil binding factor calculated in each of these species unveils the fact that they can be used as good soil binders, the binding capacity being slightly higher in *C. rotang.*

A simultaneous increase in the biomass of shoot and root with age is seen in both the species of *Calamus*. When organic carbon, available nitrogen and extractable phosphorus is significantly and positively related to the root growth in both the species, exchange acidity and exchangeable aluminium have significant positive relation with root growth in *C. thwaitesii* alone. A significant and positive relation is seen for calcium with the different root parameters in *C. rotang*. The study also reveals the presence of Ca containing root exudates in *C. rotang*. This throws light to the fact *C. thwaitesii* favours more acidic soil compared to *C. rotang.*

Chapter 7.

SUMMARY

7. SUMMARY

Calamus species, commonly called as 'rattan' are mostly trailing or climbing spiny palms with characteristic scaly fruits, classified under the subfamily Calamoideae of the family Arecaceae (Palmae) (Uhl and Dransfield, 1987). Rattans constitute an integral part of the tropical forest ecosystem and ecologically, they are the indicators of the health of tropical evergreen forests. Today, rattans are high value materials that are being over exploited and have been short in supply.

Rattans are restricted mostly to remote areas in Kerala and the broad genetic base is being reduced alarmingly. Ecosystem conservation together with large scale cultivation of rattans will guarantee the conservation of the species and genetic diversity. The Kerala Forest Department has already started cane plantations and may be extended during the coming years. But the silvicultural practices to be adopted in the field during the early stages of seedling growth is not yet standardised. This requires a knowledge about the extent and efficiency of the root system during the early stages.

The study of root system occupies a significant position due to relationship between the soil and root. On its size, type and efficiency depend the competitive ability of an individual and the success of a species in any given habitat. Knowledge of the structure and development of the root system is essential for complete understanding of the ecological requirements of each plant, which in turn forms the necessary basis for silvicultural practices. The function and activity of root system is closely linked to their normal environment, the soil. Root morphology and distribution has been identified as a balance between systematic biological mechanisms and their disruption by environmental factors, particularly changes of soil density and soil surface contours. Study of root morphology is therefore important in understanding the interaction and dynamics within the soil system.

In the study of soil-plant relation, in addition to the geometry of individual roots (length, diameter, volume and surface area) the spatial distribution of roots in the soil also is of great importance, because the orientation of root axes determines the ability of the root system to retain the plant in an upright position. It can influence the efficiency with which the soil is exploited. However, the extent of root spread could also be taken into consideration when silvicultural operations are carried out. The depth of rooting and extent of branching are important in choosing plants for soil stabilisation and water shed cover.

Root systems and root morphological components (tap roots, basal roots, adventitious roots and lateral roots) although genetically controlled, are very variable in growth and development even in optimum environments. Therefore fluctuating soil environments (Soil pH, moisture, temperature and nutrients) may have major impacts on root growth.

A given edaphic environment is the result of a multitude of interactions between the many aspects of soil. Soil properties in the rhizosphere and those at a distance from the plant may quantitatively differ which in turn may influence the root growth at these distances. Moreover, soil properties may also differ at different depths, thus being responsible for difference in root growth at different depths.

The growth and development of root system can be evaluated using different root parameters like root length, rooting density, total root weight and fine root weight. Variation in soil morphological, physical, chemical and biological properties give an idea about the nature of soil. Hence an attempt is made to find out the general growth and development of root system of two species of *Calamus, C. rotang* and *C. thwaitesii* and their growth in relation to properties of soil.

In rattans, no detailed study on root system has been carried out so far and hence not much information is available on the growth pattern, the nature of branching pattern and the spatial distribution of roots.

The study is chiefly concerned with the general form which root system can attain and distribution under relatively favourable conditions with the main objectives being

1. to study and compare the development of root system, rhizome and the spatial orientation of roots of the selected species of *Calamus* from the germination of seeds onwards
2. to determine and compare the utilization of soil by the root system
3. to compare the efficiency of the root system
4. to find out the relation, if any, between the root growth and the soil characteristics

The two commercially important rattans, *C. rotang* and *C. thwaitesii* were selected for the study. The study was conducted at the Kerala Forest Research Institute, Peechi, Kerala. The field trials were carried out at the field research station of KFRI at Veluppadam.

Mature fruits of *C. rotang* and *C. thwaitesii* were depulped and put to germination in moist sawdust. The method of germination was observed. The germinated seeds were used for further field trials.

In order to achieve the first three objectives, morphological studies of the root system of the two species of *Calamus* was carried out for 3 years by excavation of the entire root system. Observations were made once in every two months.

The different growth characters like number, length and diameter of the roots were studied as given below.

Number of main roots, laterals arising from the main roots and also sublaterals emerging from the laterals were counted. Number of root lets arising from these main roots and laterals also were recorded. The data was subjected to ANOVA in order to find variation in number of roots between the two species.

The length of the roots were measured making use of a scale and a thread. The thread was placed from the emerging point of the root till its tip. The measured thread was then placed on a scale and the length noted. The data with respect to the length of main roots, laterals and sublaterals were also subjected to analysis of variance so as to find the variation in length between the two species and was followed by comparison of their mean values. Rate of increase in length of main roots, laterals and sublaterals of the two species in each year was calculated using the formula $\frac{l_2 - l_1}{l_1}$ where l_2 is the average length of the root in a particular year, and l_1 the average length of root in the previous year.

The diameter of roots was measured using vernier calipers. Diameter of very small roots were however measured using an ocular micrometer. In order to find variation in the diameter of roots between the two species, the data was subjected to analysis of variance followed by comparison of their mean values. Rate of increase in diameter of main roots, laterals and sublaterals of the two species in each year was calculated using the formula $\frac{d_2 - d_1}{d_1}$ where d_2 is the average diameter of the root in a particular year, and d_1, the average diameter of the root in the previous year.

Regression functions were fitted for two species separately for mean total length and mean diameter of root to study the pattern of changes in the above two characters separately with the period.

The other aspects of the root system studied by excavation method were

1. Root spread
2. Soil exploited
3. Effective soil volume
4. Rooting density
5. Root intensity
6. Root surface area
7. Soil binding capacity

Horizontal distance, traversed by the root system was measured with the help of a metre scale. For this, distance between the two outermost roots in the two directions was measured every two months. Soil depth occupied by each of the main roots was also measured using a metre scale, by measuring from the collar region to their tip. In order to find out the variations in horizontal spread and vertical depth of the root system between species, the data were subjected to analysis of variance. This was followed by comparison of their mean values.

Soil exploited by the root system of the two species of *Calamus* was calculated on an yearly basis making use of the formula $\pi\left(\frac{h}{2}\right)^2 v$, where '*h*' is the mean horizontal spread of the root system at each year and '*v*' is the mean vertical depth of the roots. The two species were compared based on the soil exploited by their root system.

Effective soil volume for the two species in each year was calculated from the graph drawn by plotting exploited soil volume against rooting density at each observation period. It is that soil volume at which root density shows a sharp decline. The effective soil volume calculated for each of the species in each year was compared.

Rooting density of each of the *Calamus* species was calculated separately for each year applying the formula $\frac{R_{max}}{s}$, where 'R_{max}' is the total root length and '*s*', the soil volume exploited. This parameter was also calculated making use of the data with respect to core samples taken at the end of third year. The results obtained for two species were compared.

Root intensity of each species at the end of third year was calculated from the data with respect to core samples taken at the end of third year. A comparison between the two species was made based on this. Percentage root intensity contributed by the fine roots less than 2 mm was also calculated in each of the species by considering the number of fine roots alone. A comparison was made between the two species based on the results obtained.

Root surface area was calculated separately for roots less than 2 mm and greater than or equal to 2 mm, using the formula $2\pi r l$ where 'r' stands for radius of roots and 'l', their length. Root surface area per plant calculated for each year in the two species were compared.

Soil binding capacity for the main roots, laterals and sublaterals were separately found out using the formula $\frac{v}{r^2}$ where 'v' is the root volume and 'r' the mean radius of the roots. The root volume was found out using the formula $\pi r^2 l$ where 'r' stands for mean radius of the roots and 'l' the mean length. The results obtained for the two species were also compared.

The root system was separated from the shoot system and both were weighed separately to get the fresh weight. The plant parts were dried in an oven and the dry weights were recorded.

Root shoot relationship with respect to biomass between the two species was calculated. Shoot-root ratio of fresh and dry weight of each of species was also calculated. In order to compare the two species with respect to shoot-root ratio of fresh and dry weight, a 'Student's *t* test' was carried out for the different periods.

The biomass of root and shoot produced per year in the two species was compared. Shoot – root ratio of fresh weight and dry weight of the two species was also found out and the correlation coefficients computed.

In order to find out the relationship between the root growth and the soil characteristics, core sampling was made use of. Core samples were taken at different lateral distances (0, 10 and 30 cm) from the base of the plant at different soil depths (0-15, 15-30, 30-45 and 45-60 cm). The soil samples were then processed, the root fragments separated from them and different root parameters determined as given below.

The root fragments separated from the soil samples were weighed to obtain total root weight. They were then sieved through a 2 mm sieve to get the fine roots, which were also weighed to get the fine root weight.

Length of all the roots in the samples was estimated using Newman's line intersection method. For this a transparent plastic trough was placed over a 1cm^2 graph paper. Root fragments of each soil sample along with a certain amount of water was then poured into the trough. These were then arranged in such a manner that they do not touch one another. Since the lines of the graph paper were visible through the transparent trough, number of intersections of the root pieces with the horizontal and vertical lines on the graph paper could be counted. Root length was calculated using the formula $R = \frac{11}{14} N$, where '*N*' comprise all intercepts of roots with total length of vertical and horizontal grid lines. '*R*' was measured in terms of grid units.

Rooting density in each soil sample was calculated from the root length using the formula $\frac{l}{v}$ where '*l*' is the total root length in each sample and '*v*' is the volume of the soil present in that core sample.

The processed soil samples were used for laboratory analysis

Soil moisture and gravel content were estimated using gravimetric method. Important physical properties like texture (international pipette method) and bulk density (core method) were estimated.

The pH of soil water suspension (1:2.5) was determined using a digital type Elico pH meter.

Organic carbon content was estimated by sulphuric acid and potassium dichromate wet digestion method.

Available N was estimated by alkaline permanganate method. Available P was extracted by Bray No.1 extractant (0.03 N NH_4 F + 0.025 N HCl soil solution ratio 1 : 10; period of extraction 5 minutes) and the P content was determined calorimetrically by the ascorbic acid reduced molybdophosphoric blue colour method in hydrochloric acid systems.

Exchange acidity of the soil was estimated by titrating 1M KCl extract of soil (soil solution ratio 1:5;period of extraction 30 minutes) with standard NaOH using phenolphthalein as indicator. Exchangeable K, Na, Ca and Mg were estimated from the neutral ammonium acetate extract of the soil. 5 gm of soil was extracted with neutral normal ammonium acetate (1:15) for 10 minutes, filtered and the filtrate was used to determine K and Na using a digital type Elico (CL –361) Flame Photometer. The same filtrate was used to estimate Ca and Mg using complexometric EDTA titration.

Statistical analysis was carried out by correlation studies. Correlation coefficients between soil properties and root parameters were determined. In order to know the significance of rooting parameters at various depths and radial distances, one way analysis of variance was carried out.

The type of the seed germination and the nature of origin of roots were similar for the two species studied. Mode of seed germination was adjacent ligular.

Morphological studies of the root systems of the *Calamus* species revealed that vertical growth was predominant in rattan species during its earlier stages. The root system of a three year old seedling of *C. rotang* showed more horizontal spread compared to that of *C. thwaitesii*. However *C. thwaitesii* was provided with a root system that occupied more soil depth at the end of third year.

Root development pattern with respect to the length and diameter of roots in *Calamus* showed that both of them increased with age of the plant.

The shoot biomass showed a simultaneous increase with increase in root biomass in both the species of *Calamus.*

The soil volume exploited by the two species of *Calamus* was calculated for each year and was compared. Comparison between species showed that *C. rotang* exploited more soil volume than *C. thwaitesii.* The effective soil volume was also found to show an increase in *C. rotang* when compared to that of *C. thwaitesii.* Knowing the effective soil volume, the size of polybags to be used in nursery for raising the seedlings could be adjusted accordingly.

Rooting density of the two species, on comparison showed an increase in *C. thwaitesii* at the end of third year. Results from the core samples taken at the end of third year also agreed to this. Rooting density was found to be more in the upper 30 cm layer of soil in both the species. With respect to the lateral distances, rooting density was slightly more at 10 cm away from the base of the plant than that at the immediate basal region of the plant in *C. rotang*. Rooting density was least at a distance of 30 cm away from the base of the plant in this species. In *C. thwaitesii,* rooting density was maximum at the basal region of the plant and decreased along with an increase in the radial distances.

Root intensity in the two species was calculated by taking into consideration the number of roots present per unit area of soil. The results revealed that root intensity was more in *C. thwaitesii* compared to that of *C. rotang*. Total root intensity as well as absorbing root intensity decreased with increase in depth in both the species. When lateral distances were taken into consideration, total root intensity was maximum at 10 cm away form the base of the plant and minimum at 30 cm distance from the plant base in *C. rotang*. However, percentage of absorbing intensity was more at 10 cm lateral distance followed by 30 cm lateral distance in *C. thwaitesii.* Both total root intensity and absorbing root intensity decreased with increase in radial distance.

The presence of absorbing roots at all the radial distances studied, together with the spread of root system upto 60 cm in *C. thwaitesii* at the end of third year, suggest that basins for holding water and manure are to be opened at a radial distance of 30 cm. However in *C. rotang*, this silvicultural work should be done at a radial distance of 50 cm, since the horizontal spread of the root system in this species reached upto 90 cm. The concentration of fine roots in the upper 30 cm of soil in both species of *Calamus* again suggest the depth of these basins opened for manuring.

Root surface area per plant calculated in the two species revealed that *C. thwaitesii* had more root surface area compared to that of *C. rotang.*

Soil binding capacity was determined for both *C. rotang* and *C. thwaitesii* based on which both of them could be considered as good soil binders. However, *C. rotang* showed more soil binding capacity compared to *C. thwaitesii* at the end of 2 years.

Soil analysis was carried out in all the 280 soil samples taken by core method. Correlation studies between the different root parameters (root length, total root weight, fine root weight and rooting density) and soil properties (soil moisture, bulk density, gravel, texture, pH, organic carbon, available nitrogen, extractable phosphorus, exchange acidity, exchangeable aluminium, exchangeable calcium, magnesium, sodium and potassium) revealed that the influence of soil properties on the root parameters were more evident when the studies were made within a depth of 0-16 cm and upto a radial distance of 30 cm.

Among the different soil physical properties, in general, soil moisture and gravel were negatively correlated to the root parameters while positive correlation was seen with sand. It was revealed from the mean data of the soil properties that *C. thwaitesii* was more resistant to drought than *C. rotang*. Hence *C. thwaitesii* could be used for planting in areas of water scarcity.

Among the different soil chemical properties, influence of pH, exchange acidity, exchangeable aluminium, potassium, calcium and extractable phosphorus on the root parameters were not similar in the two species.

Soil samples of *C. thwaitesii* showed a higher pH compared to that of *C. rotang*, which means that, the former species was more acidic. Since both the species were subjected to uniform conditions, this change in pH might be probably due to the presence of certain calcium containing exudates in *C. rotang.*

When exchange acidity and exchangeable aluminium of the soil showed negative relation with the root parameters in *C. thwaitesii*, it was not so in *C. rotang*. The reason for this can be attributed to the neutralising effect of Ca containing exudates on those soil properties, in *C. rotang.*

Another noteworthy fact was the positive correlation of root parameters in *C. thwaitesii* with potassium and affinity of *C. rotang* towards Ca. Since the mean content of Ca recorded in the soil samples of both the species was more or less the same, the positive correlation of Ca with the root parameters in *C. rotang* might be due to its affinity towards divalent cations. However, *C. thwaitesii*, just as in other monocots, showed affinity towards potassium.

A knowledge of the soil properties and the effect of these on the root growth of seedlings will help in finding out the suitability of a particular species to a particular locality. Besides, an idea of the soil volume exploited by the root system and the effective soil volume of each species will be of help in raising the seedlings in suitable polybags in nursery. Knowledge of the rooting density and the root intensity of the seedlings at different soil depths and lateral distances from the plant will be of use in carrying out silvicultural operations such as mulching, opening basins for holding water, manuring etc. Thus, this study would be beneficial while raising rattans on a large scale as a plantation.

Chapter 8.

REFERENCES

REFERENCES

Al-khafaf, S., P.J. Wierenga and B.C. Williams. 1977. A floatation method for determining root mass in soil. Agron. J., 69: 1025-1026.

Alvarado, A. and F. Sterling. 1993. Evaluation of oil palm (*Elaeis guineensis*) root distribution pattern (in Deli x AVROS and a compact hybrid). Agronomia costarricense, 17 (1): 41-48.

Andrews, R.E. and E.I. Newman. 1970. Root density and competition for nutrients. Ecologia Pl. 5: 319-334.

Angelov, T. 1976. Root system distribution in bearing apple trees and methods of irrigation (in Bulgaria) Oroschcharstvo, 55: 33-37.

Anto, P.V., C. Renuka and V.B. Sreekumar. 2001. *Calamus shendurunii* - A new species of Arecaceae from Kerala, India. Rheedea, 11(1): 37-39.

Atkinson, D. 1974. Some observations on the distribution of root activity in apple trees. Plant Soil, 40: 338-342.

Atkinson, D. 1980. The distribution and effectiveness of the roots of tree crops. Horticultural Reviews, 2: 424-490.

Atkinson, D. 1983. The growth, activity and distribution of the fruit tree root system. Plant Soil, 71: 23-35.

Atkinson, D. and S.A. Wilson. 1979. The root soil interface and its significance for fruit tree roots of different ages. *In*: J.L Harley and R.S. Russell (eds.). 'The soil root interface'. Academic press. London. pp. 259-271

Atkinson, D. and S.A. Wilson. 1980. The growth and distribution of fruit tree roots: some consequences for nutrient uptake. *In*: D. Atkinson, J.E. Jackson, R.O. Sharples and

W.M. Waller (eds.) 'Mineral nutrition of fruit trees'. Butter worth, London. pp. 137-150.

Atkinson, D., D. Naylor and G.A. Coldrick. 1976. The effect of tree spacing on the apple root system. Hortic. Res., 16: 89-105.

Baldwin, J.P. and P.B. Tinker. 1972. A method for estimating the lengths and spatial patterns of two inter penetrating root systems. Plant Soil, 37: 209-213.

Baligar, V.C., N.K. Fageria and M.A. Elrashidi. 1998. Toxicity and nutrient constraints on root growth. Hort Science. 33(6): 960-965.

Banik, R. L. and F.U. Ahmed. 1986. An investigation on the roots of Bara bet (*Calamus viminalis* Willd. var. *fasciculatus* Becc.) Bano Biggyan Patrika, 15(1&2): 37-40.

Barber, S.A. and M. Silverbush. 1984. Plant root Morphology and nutrient uptake. *In*: S. A. Barber and D.R. Boulden (eds.) 'Roots, Nutrient and Water Influx, and Plant Growth'. Madison, WI: Am. Soc. Agon., pp. 65-87.

Barua, D.N., and K.N. Dutta. 1961. Root growth of cultivated tea in the presence of shade trees and nitrogenous manure. Emp. J. Exp. Agric. 29 : 287-298.

Batcheldor, A.R. and D.R. Bouldin. 1972. Technique for determining root elongation rates though soil layers of different physical and chemical properties. Agron. J., 64: 49-52.

Bavappa, K.A. and K.N. Murthy. 1961. Morphology of Arecanut palm, "The root". Arecanut J. 12(2): 65-72.

Bhaskaran. A.R. and D.C. Chakrabarty. 1965. A preliminary study on the variations in the soil binding capacity of some grass roots. Indian J. Agron., 10: 326-330.

Bhimaya, C.P., N.D. Rage and V. Srinivasan. 1956. Preliminary studies on the role of grasses in soil conservation in Nilgiris. J. Soil Water Conserv. India, 4: 113-117.

Black, C.A., D.D. Evans., L.E. Ensminger., J.L. White and F.E. Clark. 1965a. Methods of Soil Analysis. Part I. Am. Soc.Agron. Inc., Madison, Wisconsin, USA. 770p.

Black, C.A., D.D. Evans., L.E. Ensminger., J.L. White and F.E. Clark. 1965b. Methods of Soil Analysis. Part II. Am. Soc. Agron. Inc., Madison, Wisconsin, USA. 1572p.

Blaser, R. E. 1937. A rapid quantitative method of studying roots growing under field conditions. J. Am. Soc. Agron., 29: 421- 423.

Bloomberg, W. J. 1974. Two techniques for examining root distribution. Can. J. Plant Sci. 54 : 865-868.

Böhm, W. 1976. *In situ* estimation of root length at natural soil profiles. J. Agric. Sci., 87: 365-368.

Böhm, W. 1979. Methods of studying Root systems. Springer-Verlag Berlin. 188p.

Bojarczuk, K. 1997. Influence of aluminum toxicity on the development of birch (*Betula pendula* Roth.) microcuttings cultured *in vitro*. Arboretum Kornickie, 42: 217-228.

Boonstra, A.E. 1931. Pflanzenzüchtung and phlanzenphysiologie Zuchter 3 : 345 - 352.

Boonstra, A.E. 1955. Het be grip "wortelwarde". *In*: De Plantenwortel in de Landbouw. Ed. By Nederlands Geroot shap voor Landbouwwetenschap. S-Gravenhage pp. 107 - 118.

Bose, R.D. and P.D. Dixit. 1931. Studies in Indian barleys: III. The root system. Indian J. Agr. Sci., 1:98-108.

Bray, R.H. 1954. A nutrient mobility concept of soil - plant relationships. Soil Sci., 78: 9-22.

Bray, J.R. 1963. Root production and the estimation of net productivity. Can. J. Bot., 41: 65-72.

Buchhlolz, F. and E. Neumann 1964. Der Ein fluss der Bodenbearbeiting and Durgung and den Wasserhaushalt and die Durchwurzelung sandiger waldboder Branderburgs. Albercht Thaer Arch. 8: 525-536.

Burkill, I.H. 1935. A dictionary of the economic products of the Malay Peninsula. Government Printer, Malasia.

Canmore - Neumann, R., A. Silber., B. Mitchnick., S. Gilad., J., Bex-Jaacov., G.M. Little John. and H. Hettasch. 1997. Effect of pH on the development of *Leucodendron* 'Safari sunset'. Acta Horticulturae. 453: 47-52.

Care, D.A. and J.E Box. 1996. Root demographics and their efficiencies in sustainable agriculture, grasslands and forest ecosystems. *In:* Proceedings on the 5th symposium of the International Society of Root Research held during 14-18 July, 1996. Clemson University, South Carolina, USA. pp 663-671.

Cavelier, J. 1992. Fine- root biomass and soil properties in a semi deciduous and a lower montane rain forest in Panama. Plant soil, 142 : 187 - 201.

Charlton, W.A. 1983. Patterns of distribution of lateral root primordia. Ann. Bot, 51:417-427.

Charlton, W.A. 1996. Lateral root initiation. *In*: Y. Waisel, A. Eshel and U. Kafkafi (eds.) Plant Roots - The Hidden Half, Marcel Dekker Inc. New York. pp 149-173.

Clune, T.S. and Copeland, L. 1999. Effects of aluminum on canola roots. Plant Soil, 216(1-2): 27-33.

Cockroft, B. and J.C. Wallbrink. 1966. Root distribution of orchard trees. Aust. J. Agric. Res., 17: 49-54.

Collins, R.P., P.J. Gregory, H.R. Rowse, A. Morgum and B. Laecashire, 1987. Improved methods of estimating root length using a photocopier, a light box and a bar code reader. Plant Soil, 103: 277-280.

Corner, E.J.H. 1966. The Natural History of Palms. Weidenfeld and Nicolson, London. 393p.

Cornforth, I.S. 1968. Relationships between soil volume used by roots and nutrient accessibility. J. Soil Sci., 19: 291-301.

Covacevich, F., H.E. Echeverria and L.A.N. Aguirrezabal 1998. Influence of phosphorus on shoot and root growth of wheat plants. Ciencia del suelo.,16(2): 94-98.

Cronan, C.S. 1991. Differential absorption of Al, Ca and Mg by roots of red spruce (*Picea rubens* Sarg). Tree physiology, 8: 227-237.

Cronan, C.S., R. April, R. Bartlett, P. Bloom, C. Driscoll, S. Gherini, G. Henderson, J Joslin, J.M. Kelly, R. Newton, R. Parnell, H. Patterson, D. Raynal, M. Schaedle, C. Schofield, E. Sucoff, H. Tepper and F. Thornton. 1989. Aluminium toxicity in forests exposed to acidic deposition: the ALBIOS results. Water, Air, Soil Pollut., 48: 181-92.

Davis, 1961. Aerial roots in the Areca palm (*Areca catechu*, L.). Arecanut J. 12(2): 72-78.

Dexter, A. R. and J.S. Hewitt. 1978. The deflection of plant roots. J. Agric. Engng. Res., 23: 17-22.

Dhyani. K., P. Narain and R.K. Singh. 1990. Studies on root distribution of five multipurpose tree species in Doon Valley, India. Agroforestry systems, 12:149-161.

Dittmer, H. J. 1937. A quantitative study of roots and root hairs of a winter rye plant (*Secale cereale*). Am. J. Bot., 24: 417-420.

Dittmer, H. J. 1938. A quantitative study of the subterranean members of three field grasses. Am. J. Bot., 25: 654-657.

Dittmer, H. J. 1948. A comparative study of the number and length of roots produced in nineteen Angiosperm species. Bot. Gaz., 109: 354-357.

Dittmer, H. J. 1959. A method to determine the length of individual roots. Bull. Torrey Bot. Club, 86: 59-61.

Dorst, L., and A.W.M. Smeulders. 1987. Length estimators for digitized contours. Computer vision, Graphics and Image Processing, 40: 311-333.

Dransfield, J. 1974. A short guide to rattan. BIOTROP/TF/74/128, Boga, Indonesia, Regional Centre for Tropical Biology. 69p.

Dransfield, J. 1978. Growth forms of rain forest palms. *In*: P.B. Tomlinson and M.H. Zimmermann (eds). 'Tropical Trees as Living Systems'. Cambridge Univ. Press, New York. pp. 247-268

Dransfield, J. 1979a. A manual of the Rattans of the Malay Peninsula. Malaysian Forest Record. No.29, FRI, Kepong, Malaysia. 270p.

Dransfield, J. 1979b. Systematics and ecology of palms. Annual Review of Ecological Systematics, 19: 85-107.

Dransfield, J. 1997. The rattan taxonomy and ecology.. *In*: A.N. Rao and V. R. Rao. (eds.) Rattan-taxonomy ecology, silviculture, conservation, genetic improvement and biotechnology. Proceedilngs of training courses cum workshops, Saraswak, Sabah, 14-26 April 1996. pp. 1-14

Dunsworth, B.G. and J.W. Kumi. 1982. A new technique for estimating root system activity. Can. J. For. Res., 12: 1030 -1032.

Eis, S. 1974. Root system morphology of Western hemlock, Western red cedar and Douglas – fir. Can. J. For. Res., 4: 28-38.

Eissenstat, D.M. and M.M. Caldwell. 1988. Competitive ability is linked to water extraction. A field study of two arid land tussock grasses. Oeclogia, 75: 1-7.

Ellis, F.B. and B.T. Barnes. 1973. Estimation of the distribution of living roots of plants under field conditions. Plant Soil, 39 : 81-91.

Ennik, G.C. and T.B. Hoffman, 1983. Variation in the root mass of rye-grass types and its ecological consequences. Neth. J. Agric. Sci., 31: 325-334.

Ewing, R.P. and T.C. Kaspar. 1993. An accurate method for measuring lengths of washed root. Agron. Abstr., Am. Soc. Agron., Madison, WI, p.315.

Fageria, N.K., V.C. Baligar and R.J. Wright. 1997. Soil environment and root growth dynamics of field crops. Recent Research- Developments in Agronomy, 1: 15-58.

Feng-Guang Long., Luo- Yuan Pei., Yang –Peiling., Liu- Jian Li., Feng-GL., Luo-Y. P., P.L. Yang, and Liu-J. L. 1998. Effect of soil water on growth and development of primary and adventitious root of winter wheat. Acta Agriculturae Boreali Sinica . 13(3): 11-17.

Ferguson, I.B. and D.T. Clarkson, 1975. Ion transport and endodermal suberization as in the roots of *Zea mays*. New Phytol., 75: 69-77.

Fisher, J.B., K. Jayachandran and A. Stokes. 1999. Root structure and arbuscular mycorrhizal colonization of the palm *Serenoa repens* under field conditions. Plant Soil. 217(1-2): 229-241.

Fitter, A.H. 1986. Acquisition and utilization of resources. *In*: M. J. Crawl (ed.). 'Plant Ecology'. Blackwell, Oxford. pp. 375–405.

Fitter, A.H. 1987. An architectural approach to the comparative ecology of plant root systems. New phytol., 106 (Suppl.): 61-77.

Fogel, R. 1985. Roots as primary producers in below- ground ecosystems. *In*: A.H., Fitter, D. Atkinson, D.J. Read, and M.B Usher (eds.) 'Ecological Interactions in Soil - PLANTS, MICROBES AND ANIMALS'. Blackwell, Oxford. pp. 23-36

Ford, E.D. and J.D. Deans. 1977. Growth of Sitka spruce plantations: spatial distribution and seasonal fluctuations of lengths, weights and carbohydrate concentrates of fine roots. Plant Soil, 47: 463–485.

Fowkes, N. D. and J. J. Landsberg. 1981. Optimal root systems in terms of water uptake and movement. *In*: D.A. Rose and D.A. Charles-Edwards (eds.). 'Mathematics and plant physiology.' Academic Press, London. pp.109-128.

Fu – HaiQing., Duan - Aiwang., Tang – chuan Fu., Fu - HQ., Duan, A. W. and Yang, C. F. 2000. Physiological and morphological responses of winter wheat to soil moisture. Acta Agriculturae Boreali Sinica 15(1): 92-96.

Fusseder, A. 1983. A method for measuring length, spatial distribution and distances of living roots *in situ*. Plant Soil, 73: 441-445.

Fusseder, A. 1987. The longevity and activity of the primary root of maize. Plant Soil, 101: 257-265.

Gahoonia, T.S., F. Asmar, H. Giese, Gissel- Nielsen and N.E. Nielsen. 2000. Root-released organic acids and phosphorus uptake of two barley cultivars in laboratory and field experiments. European J. Agron., 12(3-4): 281-289.

Gardner, W.R. 1964. Relation of root distribution to water uptake and availability. Agron. J., 56: 41-45.

Gill, R., I.C. Burke, D.G. Milchunas and W.K. Lauenroth. 1999. Relationship between root biomass and soil organic matter pools in the short grass steppe of Eastern Colorado. Ecosystems, 2(3): 226-236.

Godbold, D. L., E. Fritz and A. Huttermann. 1988. Aluminium toxicity and forest decline. Proc. Natl. Acad. Sci., 85: 3888–3892.

Gooderham, P.T. 1969. A simple method for the extraction and preservation of an undisturbed root system from a soil. Plant Soil, 31(1):, 201-205

Goodman, A.M. and A.R. Ennos, 1999. The effects of soil bulk density on the morphology and anchorage mechanics of the root systems of sunflower and maize. Ann. Bot., 83(3): 293-302.

Gottlein, A., A. Heim, E. Matzner P.J. Gregory and P. Hinsinger. 1999. Mobilization of aluminum in the rhizosphere soil solution of growing tree roots in an acidic soil. New approaches to studying chemical and physical changes in the rhizosphere. Plant Soil, 211(1): 41-49.

Graham, J.P., D.T Clarkson and J. Sanderson. 1974. Water uptake by the roots of marrow and barley plants. Rpt. ARC Letcombe Lab for 1973. pp. 9-12.

Grey, B.S. 1969. "A study of the influence of genetic, agronomic and environmental factors on the growth, flowering and bunch production of Oil palm on the West Coast of Malaysia". Ph. D thesis, University of Aberdeen, Aberdeen. 947p.

Groff, P.A. and D.R. Kaplan. 1988. The relation of root systems to shoot systems in vascular plants. Bot. Rev., 54: 387-422.

Grosskopf, W. 1950. Bestimmung der charakteristischen Feinwurzel-Intensitäten in ungünstigen waldboden profilen und ihre oekologische Austwertung. Mitt. Bundesdforschugsanstalt Forst- Holzwirtsch. Nr., 11: 1-19.

Hackett, C. 1969. A study of the root system of barley. II Relationship between root dimensions and nutrient uptake. New Phytol., 68: 1023-1030.

Hackett, C., and B.O. Bartlett. 1971. A study of the root system of barley. III Branching pattern. New phytol., 70(2): 409-413.

Halle, F., R.A.A. Oldeman and T.B. Tomlinson. 1978. Tropical Trees and Forests: An architectural analysis. Springer – Verlag, Berlin. 441p.

Hallmark, W.B. and S.A. Barber. 1984. Root growth and morphology, nutrient uptake and nutrient status of early growth of Soyabeans as affected by soil P and soil K. Agron. J., 76: 209-212.

Harris, G. A., and G. S. Campbell. 1989. Automated quantification of roots using a simple image anlyzer. Agron. J., 81: 936-938.

Head, G.C. 1966. Estimating seasonal changes in the quantity of white unsuberized root on fruit trees. J. Hortic. Sci., 41: 197-206.

Hesse, P.R. 1971. A Text Book of Soil Chemical Analysis. John Murray Publishers Ltd., London.

Hirano, Y. and N. Hijii. 1998. Effects of low pH and aluminium on root morphology of Japanese red cedar saplings. Environ. Pollut., 101(3): 339-347.

Hoffman, W.F. and S. A. Barber. 1971. Phosphorus uptake by wheat (*Triticum aestivum*) as influenced by ion accumulation in the rhizocylinder. Soil Sci., 112: 256-262

Hoshikawa, K. 1969. Underground organs of the seedlings and the systematics of Gramineae. Bot. Gaz.,130: 192-203.

Imhoff, S., Silva-Ap-da, C.A. Tormena and A.P. da-Silva. 2000. Spatial heterogeneity of soil properties in areas under elephant-grass short-duration grazing system. Plant Soil, 219(1-2): 161-168.

Jackson, M.L. 1958. Soil Chemical Analysis. Prentice Hall Inc. Engle Wood Cliffs, N.J., USA. Reprint (1973) by Prentice Hall of India (Pvt.) Ltd., New Delhi.498p.

Jones, C. A. 1983. Effect of soil texture on critical bulk densities for root growth. Soil sci. Soc. Am.J., 47: 1208-1211.

Joslin, J.D., J.M. Kelly, M.H. Wolfer and L.E. Rustad. 1988. Elemental patterns in roots and foliage of mature spruce across a gradient of soil aluminium. Water, Air, Soil Pollut., 40: 375–390.

Jourdan, C. and H. Rey. 1997. Architecture and development of the oil palm (*Elaeis guineensis* Jacq.) root system. Plant Soil, 189(1): 33-48.

Khasawach, F.E and J. P. Copeland. 1973. Cotton root growth and uptake of nutrients : relation of phosphorous uptake to quantity, intensity and buffering capacity. Proc.Soil Sci. Soc. Am., 37: 250 - 254.

Kirchhof, G. 1992. Measurement of root length and thickness using a hand- held computer scanner. Field crops Res., 29: 79-88.

Kirchhof, G., J. Blackwell and R. Smart. 1991. Growth of Vineyard roots on segimentally ameliorated acidic subsoils. Plant Soil, 134: 121-126.

Klepper., B. and, R.W. Rickman. 1990. Modeling crop root growth and function. Adv. Agron., 44: 113-131.

Klepper, B., R.K. Belford and R.W. Rickman. 1984. Root and shoot development in winter wheat. Agron. J., 76: 117-122.

Kolesnikov, V. A. 1962. Untersuchungen uber does Wurzel system und die Ernahrung der obstgehölze. Arch. Gartenban 10: 447- 459.

Kolesnikov, V. A. 1971. The root system of fruit plants . Moscow, USSR: Mir Publishers, 269 p.

Köpke, U. 1979. Ein vergleich Von Feldmethoden Zur Bestimmung des Wurzelwachstums bei landwirtschaftlichen Kulturpflanzen. Diss. Agric. Göttingen.

Korikanthmath. V.S. 1998. Effect of moisture stress on growth of cardamom (*Elettaria cardamomum* Maton.) water and nutrient management for sustainable production and quality of spices. *In*: Gowda, S.J.A., K.S. Krishnamurthy, A.K. Sadanandan, K.S. Krishnamurthty and K. Kandiannan (eds.) Proceedings of the National seminar, Madikeri; Karnataka, India, 5-6 October 1997. pp. 158-160.

Kozlova, A. G. 1973. Characteristics of palm root system development during the 1st year. 1zv Akad Nauk Turka Ssr Ser Biol Nauk, 5: 79-83.

Krieter, M. 1986. Studies on soil properties and root distribution on roadside tree sites. (Lime) Gratenamt, 35 (11): 676 - 678.

Lakshmana, A. C. 1993. Rattans of South India, Evergreen publishers. 180p.

Lang, A.R.G. and F.M. Melhuish. 1970. Lengths and diameters of plant roots in non-random populations by analysis of plane surfaces. Biometrics, 26: 421-431

Lav-Bhushan., P.K. Sharma and L. Bhushan. 1999. Effect of depth, bulk density and aeration status of root zone on productivity of wheat. J. Ind. Soc. Soil Sci., 47(1): 29-34.

Leonard, J. 1957. Genera des Cynometreae et des Amherstieae africaines (Leguminosae – Caesalpinioidae). Essaide blastogenie appliquee a la systematique. Mean. Acad. Roy Belg., Cl. Sci., 30(2): 1-314

Luo-HuiMing., T. Watanabe, T. Shinano, T. Tadano and H. M. Luo. 1999. Comparison of aluminum tolerance and phosphate absorption between rape (*Brassica napus* L.) and tomato (*Lycoperscium esculentum* Mill.) in relation to organic acid exudation. Soil Sci. Plant Nutr., 45(4): 897-907

Lupton, F. G. H., R.H. Oliver, F.B. Ellis. B.T. Barnes, K.R. Howse. P.J. Welbank and P.J. Taylor. 1974. Root and shoot growth of semi-dwarf and taller winter wheats. Ann. Appl. Biol., 77: 129-144.

Lyford, W. and B. F. Wilson. 1966. Controlled growth of forest tree roots. Technique and application. Harvard University Petersham. Mass., USA. Harvard For pap. No. 16. 12pp.

Mac Donald, I. 1997. Studies on the root systems of *Bixa orellana*. African crop science journal, 5(4): 413-418.

Mackie-Dawson, L.A. and D. Atkinson. 1991. Methodology for the study of roots in field experiments and the interpretation of results. *In*: D. Atkinson (ed.). 'Plant Root Growth: An Ecological Perspective'. Blackwell scientific, London. pp. 25 – 47.

Mahabale, T.S. 1982. Palms of India. Spicer Memorial College, Pune. 245p

Mahabale, T.S. and Nandini Shirke. 1967. The genus *Caryota* in India. J. Bom. Nat. Hist. Soc., 64(3): 462-487.

Marsh, B.B., 1971. Measurement of length in random arrangements of lines .J. Appl. Ecol., 8: 265-267.

Mathur, H.N., R.P. Singh and K.C. Sharma. 1982. *Populus ciliata* – A promising tree species for soil conservation in hilly areas. The Indian For., 108(9): 599-604.

Mc Cully, M.E. and M.J. Canny, 1985. Localisation of translocated ^{14}C in roots and root exudates of field-grown maize. Physiol. Plant, 65: 380-392.

Mc Kell, M.C., M.A. Wilson and B.M. Jones, 1961. A floatation method for easy separation of roots from soil samples. Agron. J., 53: 56-57.

Mc Minn, R.G. 1963. Characteristics of Douglas- fir root systems. Can J. Bot., 41: 105-122.

Melhuish, F.M. 1968. A precise technique for measurement of roots and root distribution in soils. Ann. Bot., (N.S.) 32: 15-22.

Melhuish, F.M and A. R. G. Lang. 1968. Quantitative studies of roots in soil. 1. Length and diameter of cotton roots in clay loam soil by analysis of surface-ground blocks of resin impregnated soil. Soil Sci., 106: 16-22.

Melhuish, F.M and A. R. G.Lang. 1971. Quantitative studies of roots in soil. II. Analysis of non-random populations. Soil Sci., 112(3): 161-166.

Mohankumar, B. and V.N. Divakara. 2001. Proximity, clump size and root distribution pattern in bamboo : A case study of *Bambusa arundinacea* (Retz.) Willd., Poaceae, in the Ultisols of Kerala, India. J. Bamboo and rattan, 1(1): 43-58.

Mohapatra, A.R., N.T. Bhat and K.B. Abdul Khader. 1971. Principles and practices of fertilizer use in Arecanut. Arecanut and Spices Bulletin, 11(4): 1-3.

Morita, S., S. Yamada and J. Abe. 1995. Analysis of root system morphology in rice with reference to varietal differences at the ripening stage. Japan. J. Crop Sci., 64(1): 58-65.

Mothes, K. 1956. Die Wurzel der pflanzen – eine chemische werstatt beslonderer Art. Abh. Dtsch. Akad. Wiss. Berl., Kl. Chemie, Geol. U. Biol., 6: 1-16.

Nadelhoffer, K. J., R. Norby, A. Fier and R. Jackson. 2000. The potential effects of nitrogen deposition on fine root production in forest ecosystem. New Phytol., 147(1): 131-139.

Nambiar, E. K. S. 1983. Root development and configuration in intensively managed radiata pine plantation. Plant Soil, 71: 37-47.

Nardi, S. and G. Concheri. 2000. Mobilization of the soil organic fraction by the root exudates of forest and crop plants. Monti – e – Boschi, 51(3-4): 51-56.

Nasi, R.P. 1994. Some aspects of root architecture and growth strategies of Malaysian rattans. Acta Oecol., 15(6): 753-766.

Nass, H.G. and M.S. Zuber. 1971. Correlation of Corn (*Zea mays* L.) roots early in development to mature root development. Crop Sci., 11(5): 655-658.

Newman, E.I. 1966. A method of estimating the total length of root in a sample. J. Appl. Ecol., 3: 139 -145.

Newman, E.I. 1969. Resistance to water flow in soil and plant : 1. Soil resistance in relation to amounts of root: the vertical estimates. J. Appl. Ecol., 6: 1-12.

Newman, E.I. and R.E. Andrews. 1973. Uptake of phosphorus and potassium in relation to root growth and root density. Plant Soil, 38: 49 - 69.

Newman, P.R., and L.E. Moser. 1988. Seedling root development and morphology of cool-season and warm season forage grasses. Crop. Sci., 28:148-151.

Neumann, G., A. Nasonneau, N. Langlade, B. Dinkelaker, C. Bengeler, V. Romheld and E. Nartrionia. 2000. Cluster roots : their physiology, ecology and developmental biology. Ann. Bot., 85(6): 909–919.

Nitta, Y., Y. Yamamato and N. Ichiryu. 1996. Studiles on the formation of the crown root primordia of rice plant. II. Formation of the crown root primordia in the lower part of unelongated stem. Japan. J. Crop Sci., 65: 465-472.

Nunez-U-MC., Bisbal-EC-de .and de-Bisbal-EC. 1999. Effect of soil compaction on some morphological parameters of maize root development. Agronomia-Tropical-Maracay, 49(1): 93-106.

Nutman, E.J., 1934. The root - system of *Coffea arabica* III. The spatial distribution of the absorbing area of the root. Emp. J. Exp. Agric., 2: 293-302.

Nye, P.H. and P. B. Tinker. 1969. The concept of a root demand coefficient. J. Appl. Ecol., 6: 293–300.

Nye, P. H. and P. B. Tinker, 1977. Solute movements in the soil- root system. Studies in Ecology. Vol.4, Blackwell scientific publication, Oxford.

Ostonen, I., K. Lohmus and R. Lasn. 1999. The role of soil conditions in fine root ecomorphology in Norway spruce (*Picea abies* (L.) Karst) . Plant Soil, 208(2): 283-292.

Pabin, J., J, Lipiec, S.Wlodek, A. Biskupski and A. Kaus. 1998. Critical soil bulk density and strength for pea seedling root growth as related to other soil factors. Soil Till. Res., 46(3-4): 203-208.

Pan, W. L. and R.P. Bolton. 1991. Root quantification by edge discrimination using a desktop scanner. Agron. J., 83: 1047-1052.

Paolillo, A.N., J.R.S., Scholberg, L.R., Parsons, T. A. Wheaton and K.T. Mongan,. 1999. Water and nitrogen status modify root growth of two citrus root stock seedlings. Proceedings of the 112th Annual meeting of the Florida State Horticultural Society, Stuart, Florida, USA, 31 October – 2 November, 1999. pp. 18-22.

Pavlychenko, T.K. 1937a. Quantitative study of the entire root systems of weed and crop plants under field conditions. Ecology, 18: 62 - 79.

Pavlychenko, T.K. 1937b. The soil-block washing method in quantitative root study . Can. J. Res., (Sect. C) 15: 34-57.

Petcu, G., E. Petcu, M. Terbea, I. Chirnogeanu and D. Musat, 1997. Some aspects of mineral nutrition of maize in relationship to physical and chemical properties of soil. Probleme-de-Agrofitotehnie-Teoretica-Si-Aplicata. 19(2): 29 - 40.

Polomski, J. and N. Kuhn 1998. Root systems. Paul Haupt A G Bern; Switzerland. 290 p.

Pulgarin, A., J. Navascues. P.J. Casero and P.G. Lloret. 1988. Branching pattern in onion adventitious roots. Am. J. Bot., 75(3): 425-432.

Raper, C. D. Jr. and S.A. Barber., 1970. Rooting systems of soyabeans. Differences in root morphology among varieties. Agron. J., 62(5): 581-584.

Reicosky, D. C., R.J. Millington and D.B. Peters. 1970. A comparison of three methods for estimating root length. Agron. J., 62(4): 451-453.

Reiter, H., M. Alcubilla and K.E. Rehfuess. 1983. Site studies of fir die back: development and mineral contents of silver fir roots in relation to health and soil . Allgemeine – Forest – und – Jagdzeitung, 154(4/5): 82-92

Renuka, C. 1992. Rattans of the Western Ghats : a taxonomic manual. Kerala Forest Research Institute, Peechi. 61p.

Renuka, C. 1999. Palms of Kerala. Kerala Forest Research Institute, Peechi, Kerala, India. 72p.

Reynolds, E. R. C. 1970. Root distribution and the cause of its spatial variability in *Pseudotsuga taxifolia* (poir.). Britt. Plant Soil, 32: 501 - 517.

Richards, B.G., and E.L. Greacen. 1986. Mechanical stresses on an expanding cylindrical root analogue in granular media. Aust. J. Soil Res., 24: 393-404.

Riley, D. and S.A. Barber. 1971. Effect of ammonium and nitrate fertilization on phosphorus uptake as related to root-induced pH changes at the root-soil interface. Proc. Soc. Soil Sci. Am., 35: 301-306.

Riopel, J. L. 1966. The distribution of lateral roots in *Musa acuminata*. Am. J. Bot., 53(4): 403 -407.

Roberts, J. 1976. A study of the root distribution and growth in a *Pinus silvestris*, L. (Scots Pine) plantation in East Anglia. Plant soil, 44: 607 – 621.

Russell, R.S. 1977. Plant Root Systems: Their function and interaction with the soil. London: Mc Graw Hill, London. 298p.

Saakov, S. R. 1954. Palms and their cultivation in the U.S.S.R. Sci., Acad. Moscow.

Schulze, E.D. 1983. Root-shoot interactions and plant life forms Neth. J. Agric. Sci., 4: 291-303.

Schuurman, J. J. and M.A.J. Goedewaagen. 1971. Methods for the examination of root systems and roots. Wageningen; Pudoc 2nd ed.

Seubert, E. 1997. Root anatomy of palms 1. *Coryphoideae* Flora-Jena 192(1): 81-103.

Singh, B. P. and U. M. Sainju. 1998. Soil physical and morphological properties and root growth. Hort. Science, 33(6): 966-971.

Smucker, A.J.M. 1993. Soil environmental modifications of root dynamics and measurement Annu. Rev. Phytopathol., 31: 191 – 216.

Spencer, K. 1951. Tomato root distribution under furrow irrigation Aust. J. Agric. Res., 2: 118-125.

Stevenson, D. S. 1967. Effective soil volume and its importance to root and top growth of plants. Can. J. Soil Sci., 47: 163 -174.

Stoffella, P.J., A.H. Beany, D.I. Leskovar and J.N. Crane. 1998. Seedling root systems of vegetable crops: development, genotypic variability, and influence by environmental conditions. Proceedings of the inter American Society for tropical Horticulture, Barquisimeto, Venezuela, 27 September – 2 October 1998, 42: 351-354.

Subbiah, B.V. and G.L.A. Asija, 1956. A rapid procedure for the estimation of available nitrogen in soils. Curr. Sci., 25: 259-260.

Tan, K.S. 1983. Root system - 'The Botany of Oil Palm'. Incorporated society of planters, Malaysia. pp. 12-14.

Taylor, B.K. and F.H. Goubran, 1976. The phosphorus nutrition of the apple tree. II. Effects of localized phosphate placement on the growth and phosphorus content of split root trees. Austral. J. Agr. Res., 27: 533-539.

Taylor, H. M. and B. Klepper. 1973. Rooting density and water extraction patterns for corn (*Zea mays* L.) Agron. J., 65(6): 965-968.

Taylor, H. M. and B. Klepper. 1975. Water uptake by cotton root systems: an examination of assumptions in the single root model. Soil Sci., 120: 57-67.

Tennant, D., 1975. A test of a modified line intersect method of estimating root length. J Ecol., 63: 995-1002.

Tinker, P. B. 1976. Soil requirements of the Oil Palm. *In*: R.H.V Corley, J, J. Harder and B.J. Wood (eds.) ' Developments in Crop Science, Oil Palm Research'. Elseviear Scientific Publishing Company, Amsterdam. pp. 165-181.

Tomlinson, P.B. 1961. Anatomy of Monocotyledons, II. Palmae. Oxford Univ. Press, London. 453p.

Tomlinson, P. B. 1970. Monocotyledons – towards an understanding of their morphology and anatomy. *In*: R.D. Preston (ed.). 'Advances in Botanical Research'. New York, Academic Press. pp. 207–309.

Troll, W. 1937. Vergleichende Morphologic dea boheeen pflarzen. Berlin Borntraeyer, Band 1, Teil.1.

Tromp, J. 1977. Growth and mineral nutrition of apple fruits as affected by temperature and relative air humidity. *In*: J.J. Lansberg and C.V. Cutting (eds.). 'Environmental effects on Crop physiology'. London Academic Press. pp 101-117.

Troughton, A. 1960. Further studies on the relationship between the shoot and root systems of grasses. J. Br. Grassl. Soc., 15: 41-47.

Troughton, A. and W.J. Whittington. 1969. The significance of genetic variation in root systems. *In*: W.J. Whittington (ed.). 'Root growth'. London, Butterworth. pp. 296-314.

Uhl, N.W. and J. Dransfield, 1987. Genera Palmarum – A classification of palms based on the work of Harold E. Moore Jr. The L. H. Bailey Hortorium and the International Palm Society. Allen Press, Lawrence, Kasas. 610p.

Veresoglou, D.S. and A.H. Fitter. 1984. Spatial and temporal patterns of growth and nutrient uptake of five coexisting grasses. J. Ecol., 72: 259-272.

Voorhees, W. B., Amemiya Min, R. R. Allmaras and W. E. Larson. 1971. Some effects of aggregate structure heterogeneity an root growth. Proc.Soil Sci. Soc. Am., 35(4): 638-643.

Wagatsuma, T. 1983. Effect of non – metabolic condition on the uptake of Aluminium by plant roots. Soil sci. Plant Nutr., 29: 323 – 333.

Walkley, A. and I.A. Black. 1934. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci., 37: 29-34.

Watanabe, P.S. and S.R. Olsen. 1965. Test of an ascorbic and method for determining phosphorus in water and $NaHCO_3$ extracts from soil. Proc.Soil Sci. Soc. Am., 29: 677-678.

Weaver, J. E. 1926. Root development of field crops Mc Graw- Hill, New York, 291p.

Whitmore, T. C. 1973. Palms of Malaya. Oxford Univ. Press, London. 132p.

Wiersum, L. K. 1957. The relationship of the size and structural rigidity of pores to their penetration by roots. Plant Soil, 9: 75 - 85.

Wiersum,L. K. 1961. Utilization of soil by the plant root system. Plant Soil, 15: 189-192.

Wiersum,L. K. 1962. Uptake of nitrogen and phosphorous in relation to soil structure and nutrient mobility. Plant Soil, 16: 62-70.

Williams, R. D. 1962. On the physiological significance of seminal roots in perennial grasses. Ann. Bot. (N.S), 26(102): 129-136.

Willis, A.J. 1973 Introduction to plant ecology; A guide for beginners in the study of plant communities. Rev. ed.; George Allen and Unwin, London.237p.

Wilson, S.A. and D. Atkisnson. 1979. Water and mineral uptake by fruit tree roots. *In*: A. Riedacker and J. Gagnaire-Michard (eds.) Root physiology and symposia. Proc. IUFRO Symp. Sept. 11-15, 1978, CNRF. Nancy, France. pp. 372-382.

Wright, J. O. 1951. Unusual features of the root system of the oil palm in West Africa. Nature , 168: 7 - 48.

Yuan, T.I. 1959. Determination of exchangeable hydrogen in soils by titration method. Soil Sci., 88: 164-167.